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I, ANNA MAIJA MADL, ACTING TEAM LEADER EXAMINATION SUPPORT & SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. PQ 1305 for a patent by SILVERBROOK RESEARCH PTY LTD filed on 30 June 1999.

WITNESS my hand this
Fifteenth day of May 2000

7

A. M. Madl.

ANNA MAIJA MADL
<u>ACTING TEAM LEADER</u>
<u>EXAMINATION SUPPORT & SALES</u>

AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant(s):

SILVERBROOK RESEARCH PTY LTD

Invention Title:

A METHOD AND APPARATUS (HYBRID03)

The invention is described in the following statement:

A METHOD AND APPARATUS (HYBRID02)

Field of the Invention

The present invention relates to the construction of a ink supply cartridge for the supply of ink and control signals to a pagewidth inkjet printhead.

Background of the Invention

Recently, for example, in PCT Application No. PCT/AU98/00550 the present applicant has proposed a pagewidth inkjet printing device which utilizes micro-electromechanical (MEMS) processing techniques in the construction of a thermal bend actuator type device for the ejection of fluid from a nozzle chamber.

Micro-electromechanical systems are often commercially constructed utilising standard water scale semi-conductor fabrication processing techniques and they are becoming increasingly popular due to their uniqueness in allowing for microscopic scale mechanical devices to be formed which have unique operational characteristics.

MEMS devices are becoming widely used for sensing, ink jet printing, micro-fluidics and micro-electronics.

For a general survey of field and prior art in relation thereto, reference is made to "The Broad Sweep of Integrated Micro-Systems" by S. Tom Picraux and Paul McWhorter in IEEE Spectrum, December, 1998 at pages 24 to 33.

Any compact but fragile page width printhead is likely to operate on the dimensions of microns and require highly accurate registration with an external world such as with an ink supply. With a full color ink supply, multiple ink channels will have to be formed on a micron scale adjacent the printhead. This is likely to require high quality micro-machined parts. An ink supply conduit, on the other hand, is likely to be also desirably formed at a much coarser scale with much larger ink channels. Further, the

construction of the ink supply conduits is likely to be extremely complex.

Summary of the Invention

It is an object of the present invention to provide a simplified form of printhead carriage unit for carriage of a printhead segment.

In accordance with a first aspect of the present invention, there is provided a printhead carriage unit comprising: a slot for the insertion of an ink ejection printhead having a series of ink supply holes along a back surface thereof and a series of ink ejection nozzles on a front surface thereof; an abutment edge for abutment against other printhead carriage units such that the ink ejection printheads of adjacent carriage units are able to print a contiguous line.

Adjacent printhead carriage units can include overlapping printhead portions such that the contiguous line can be formed from the ink ejection nozzles of either adjacent printhead. The overlap can be about 1 millimeter. The abutment edge mates with a second printhead carriage unit rotated substantially 180 degrees with respect to the first printhead carriage unit.

The unit further preferably can include a series of alignment slots for providing fine scale adjustment of the position a first printhead carriage unit relative to a second printhead carriage unit. A tape automated bonded series of control wires interconnected to the ink ejection printhead can also be provided. The unit can be formed as a single injection moulded article. moulding.

Brief Description of the Drawings

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 illustrates an exploded perspective of the preferred embodiment;

Fig. 2 illustrates a sectional view through the preferred embodiment;

Fig. 3 illustrates a perspective view of the frame of the preferred embodiment;

Fig. 4 illustrates a back perspective view of the printhead carriage unit of the preferred embodiment;

Fig. 5 illustrates a back perspective view, partly in section, of the printhead carriage unit of the preferred embodiment;

Fig. 6 illustrates a front perspective view of the printhead carriage unit of the preferred embodiment;

Fig. 7 illustrates one form of injection moulding of the printhead carriage unit;

Fig. 8 illustrates a perspective view of the printhead carriage unit including printhead and TAB film;

Fig. 9 illustrates a first end view of a connector plug;

Fig. 10 illustrates a sectional view through the line A-A' of Fig. 9;

Fig. 11 illustrates a side view of the connector plug; and

Fig. 12 illustrates a second end view of the connector plug.

Description of Preferred and Other Embodiments

The preferred embodiment comprises an ink supply mechanism to supply an ink jet printing system such as that disclosed in Australian provisional patent number PP9223 entitled "A Method and Apparatus (IJ46P2)" filed 16 March, 1999 by the present applicant the contents of which are hereby specifically incorporated by cross-reference. The ink jet printing system disclosed in the afore-mentioned patent specification and known generally by the term "MEMJET" is also described in the attached Appendix A which provides a general discussion of the construction of a MEMJET device and its uses.

In the preferred embodiment there is provided a ink jet printhead ink supply mechanism which supplies 4 color inks (Cyan, Magenta, Yellow and Black) to a back surface of a series of print head chips. Each printhead chip consists of a 2cm by 1mm length of 4 rows of color ink ejection nozzles constructed in accordance with the aforementioned MEMJET description.

Turning now to Fig. 1 and Fig. 2, in Fig. 1 there is illustrated an exploded perspective of the ink supply mechanism which is based around an aluminum extruded frame 2 which is of indeterminate length depending upon requirements. The frame 2 includes 4 ink supply channels 5-8 down which the different colored inks flow from an interconnection placed at one end, and is shown in perspective in Fig. 3. As can best be seen from the sectional view of Fig. 2, in each cavity 5-8 the ink flows to the surface of a metal shim 9. The metal shim 9 includes a series of slots or holes 11 of approximately 2mm by 2mm dimensions. The shim 9 can be 'snap fitted' to mate with the frame 2 by mating with edges 12, 13. A glue can also be provided on the surface of shim 9 to provide proper sealing between the ink supply channels.

After flowing through the shim holes, the ink flows into one of a series of abutted printhead carriage units 15 - 17. Although each printhead carriage unit includes an associated tape automated bonded (TAB) film18, only one is shown in Fig. 1. The advantage of decoupling the ink flow down the frame 2 with that down the printhead carriage unit is that the resolution of the two technologies required for operation can also be decoupled. Hence the frame 2 can be formed from extruded aluminum and the printhead carriage unit can be formed from injection moulded plastic.

The printhead carriage unit is responsible for the distribution of ink to the back surface of the printhead and consists of a series of ink supply channels to achieve

this goal. In Fig. 4 there is illustrated the back surface of the printhead carriage unit 15 which shows the series of apertures 20. Fig. 5 illustrates a sectional view of the printhead carriage unit 15 showing the flow of ink to a front surface 21 thereof which is more clearly illustrated in Fig. 6.

In Fig. 7 there is illustrated the printhead carriage unit 15 and a series of injection moulding pieces 22 - 28 which can be utilized in its formation.

Turning now to Fig. 8, a 2cm long MEMJET printhead 30 is inserted in the front of the printhead carriage unit 15 and a TAB strip 18 attached to one edge. The arrangement of Fig. 8 can be separately tested for proof of operation by a separate machine. Once shown to be operational, a vacuum picker can be utilized to attach to surface 31 and two peg inserted in slots 32, 33 to provide positioning. Returning to Fig. 1, the printhead carriage unit 15 is then inserted into the shim 9 and positionally utilizing an optical alignment of markers on the printhead surface so that the printhead 30 is aligned with adjacent printheads of adjacent printhead carriage units e.g. 16 so as to provide a 1 millimeter overlap between the ink ejection nozzles of one printhead and those of an adjacent printhead. This overlap allows for gradual dithering between the printheads and the printhead edges so as to reduce the likelyhood of edge effects due to variations in adjacent printheads.

As can be seen from Fig. 1, the printhead carriage units have an alternating 180 degree rotation relative to one another and can be abutted together. This is a result of the mating between the bottom surface of the printhead carriage unit (illustrated in Fig. 4) and the frame 2. This allows for the usage of small overlapping printhead segments which allow for dramatic increases in yields.

The TAB film 18 is wrapped around the surface of the frame 2 and attached to a printhead controller printed

circuit board (PCB) 40 which includes circuitry for controlling the printhead. The PCB 40 is slotted in to the back surface of the frame 2.

Depending on the extruded length of the frame 2, at least one end of the frame 2 contains an ink supply plug which is inserted in the cavities 5-8 for the supply of ink. Fig. 9 to Fig. 12 illustrate one form of plug for mating with the end surface of frame 2 with Fig. 9 illustrating a first end view, Fig. 10 illustrating a sectional view through the line A-A′ of Fig. 9, Fig. 11 illustrating a side view and Fig. 12 illustrating a second end view. The end 41 is designed to have a mating plug with four ink supply tubes inserted therein for supply of ink to the frame cavities.

It will therefore be evident that the arrangement discussed provides for a highly effective form of ink supply arrangement for supplying ink to a series of ink jet printheads in a highly effective manner.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

We Claim:

1. A printhead carriage unit comprising:

a slot for the insertion of an ink ejection printhead having a series of ink supply holes along a back surface thereof and a series of ink ejection nozzles on a front surface thereof;

an abutment edge for abutment against other printhead carriage units such that said ink ejection printheads of adjacent carriage units are able to print a contiguous line.

2. A unit as claimed in claim 1 wherein adjacent printhead carriage units include overlapping printhead portions such that said contiguous line can be formed from the ink ejection nozzles of either adjacent printhead.

3. A unit as claimed in claim 2 wherein said overlap is substantially 1 millimeter.

4. A unit as claimed in any previous claim wherein said abutment edge mates with a second printhead carriage unit rotated substantially 180 degrees with respect to the first printhead carriage unit.

5. A unit as claimed in any previous claim wherein said unit further includes a series of alignment slots for providing fine scale adjustment of the position a first printhead carriage unit relative to a second printhead carriage unit.

6. A unit as claimed in any previous claim further comprising a tape automated bonded series of control wires interconnected to said ink ejection printhead.

7. A unit as claimed in any previous claim wherein said unit is formed as a single injection moulded article. moulding.

8. A printhead carriage unit substantially as hereinbefore described with reference to the accompanying drawings.

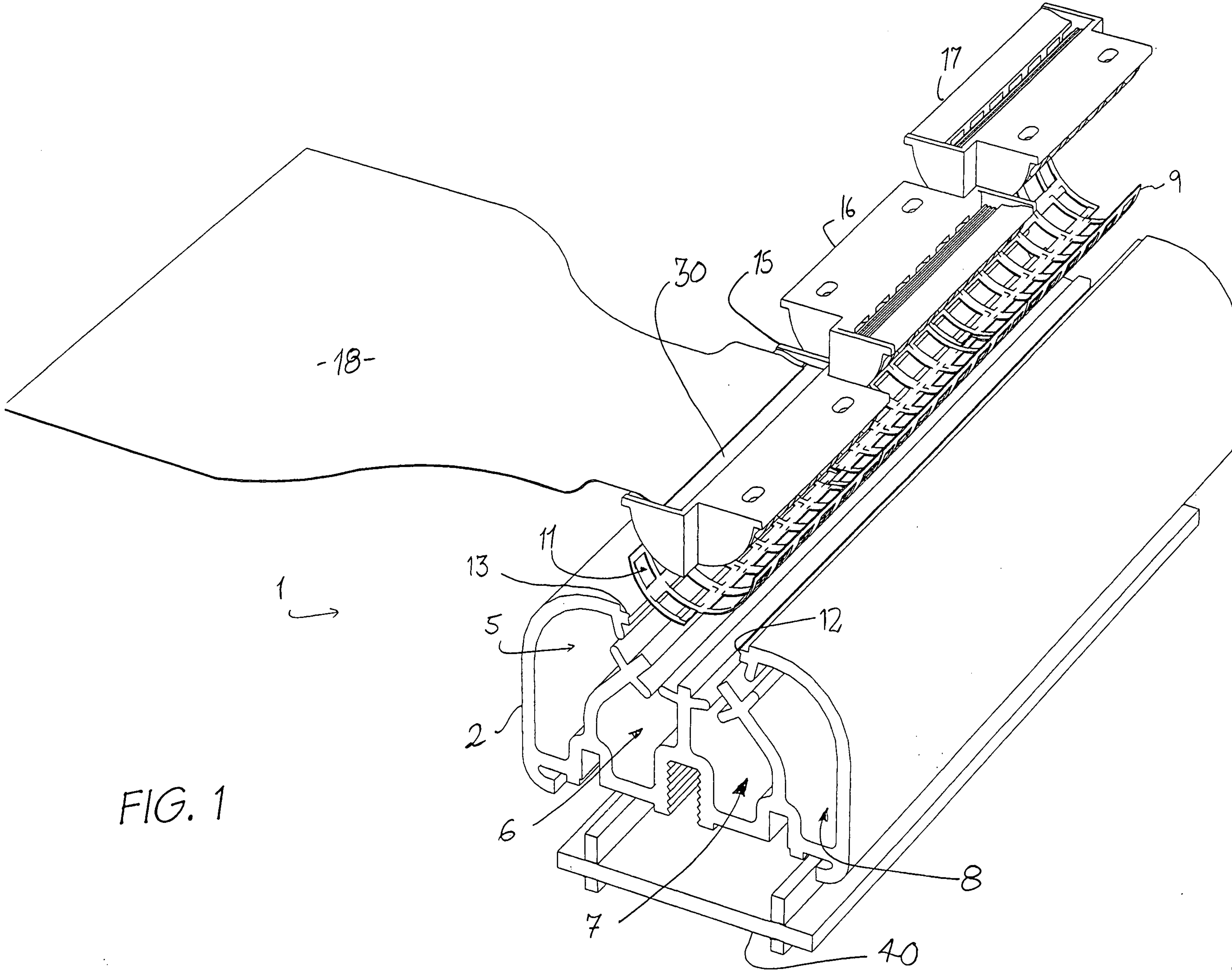


FIG. 1

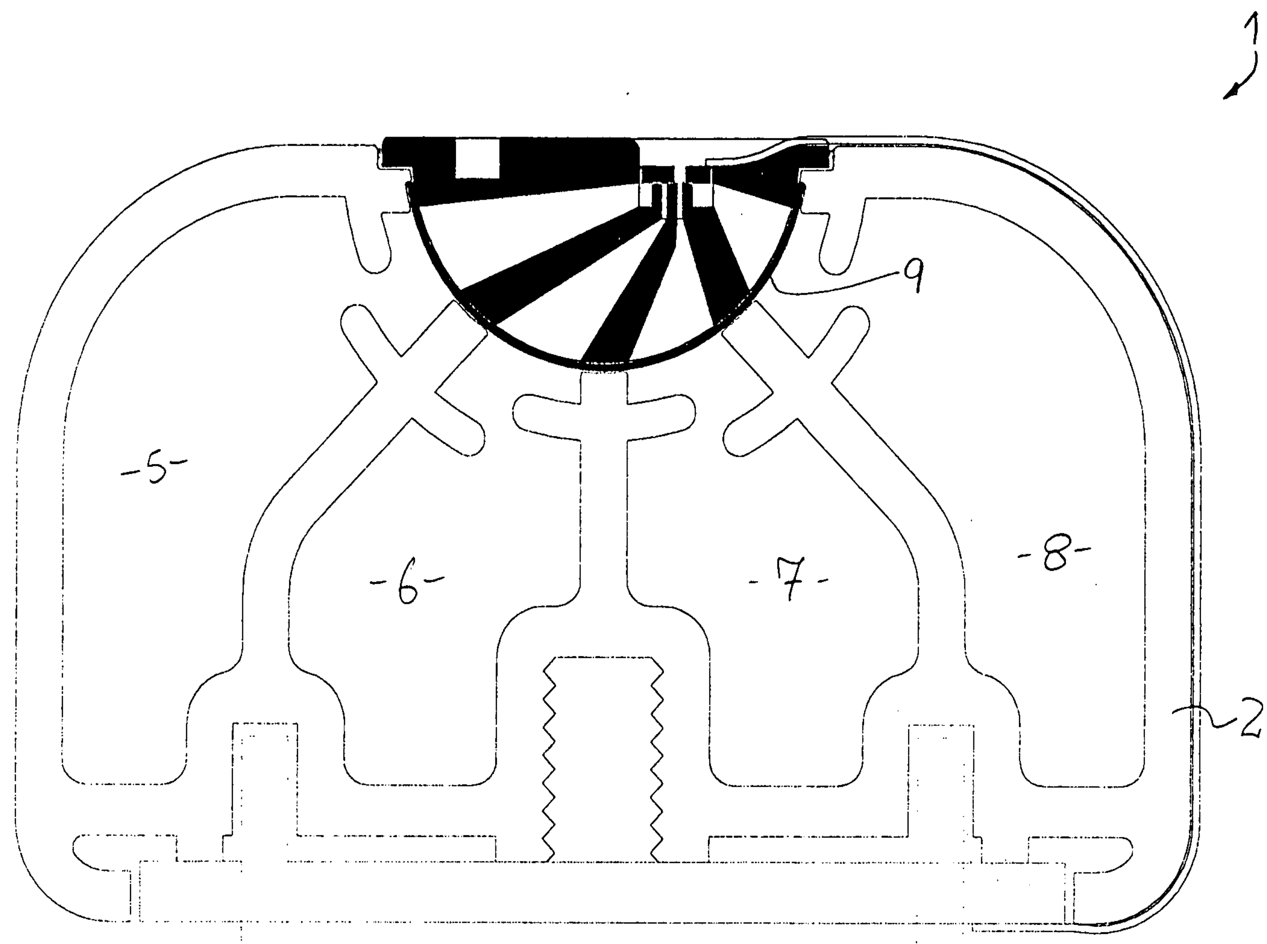


FIG. 2

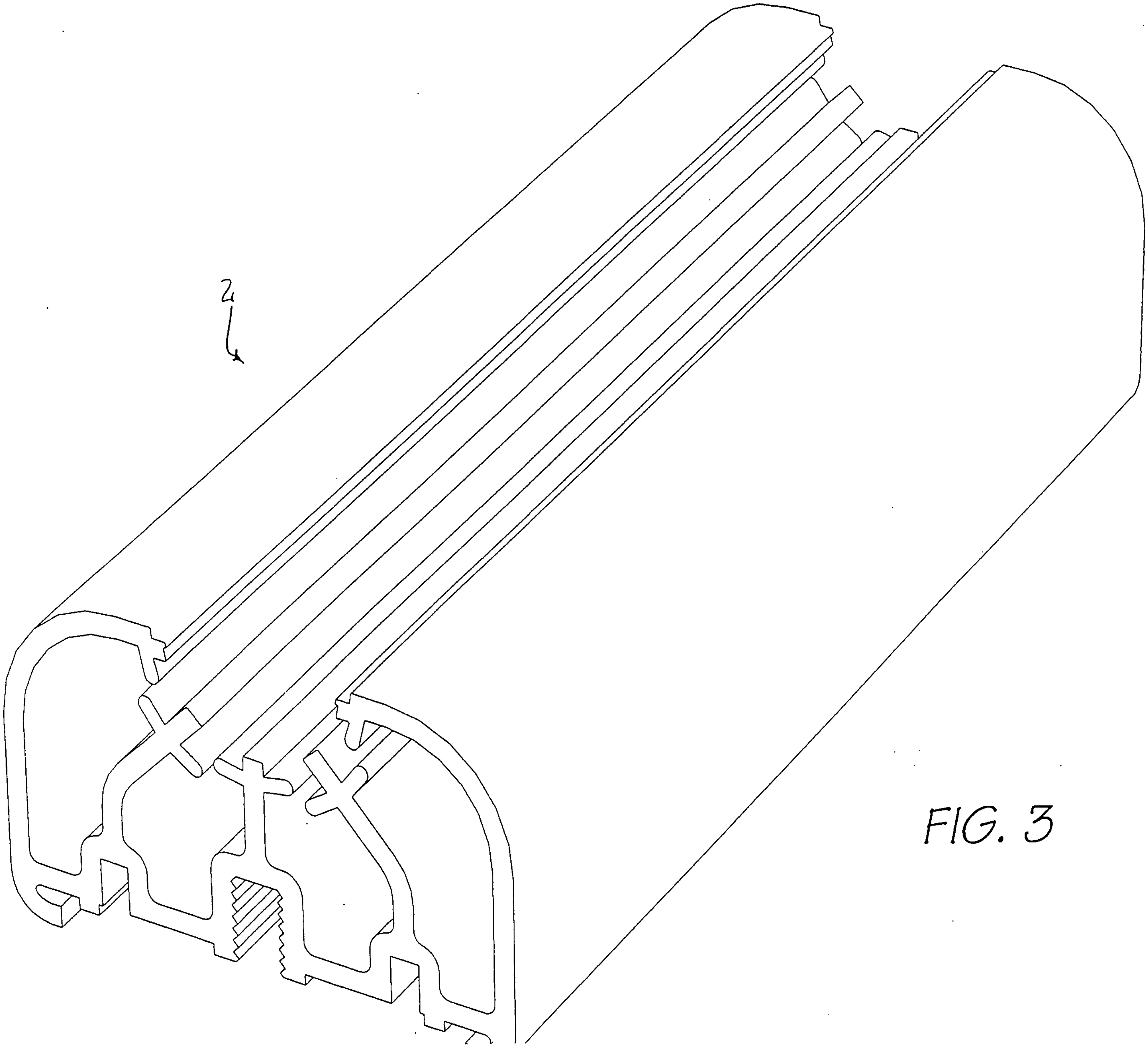


FIG. 3

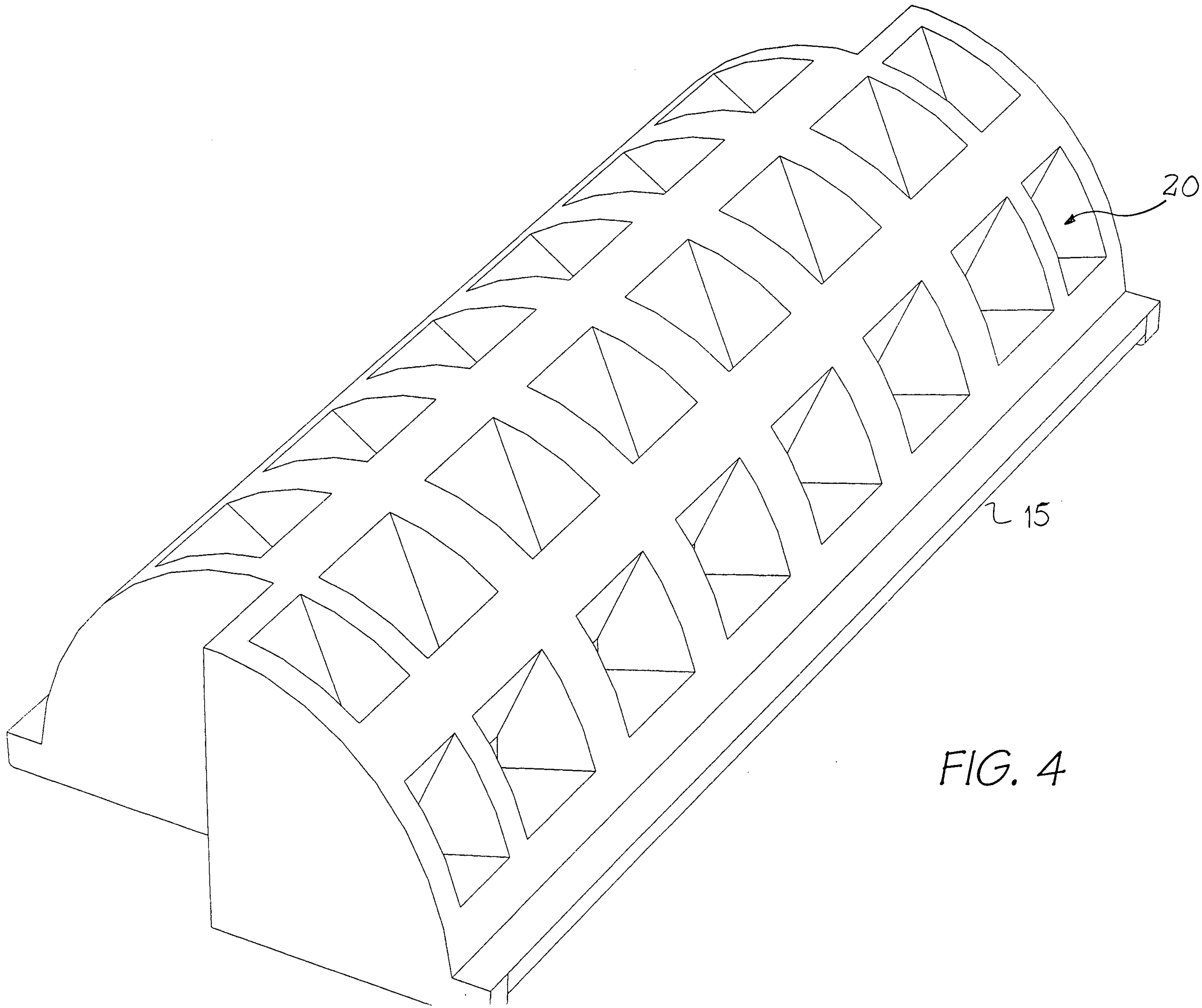


FIG. 4

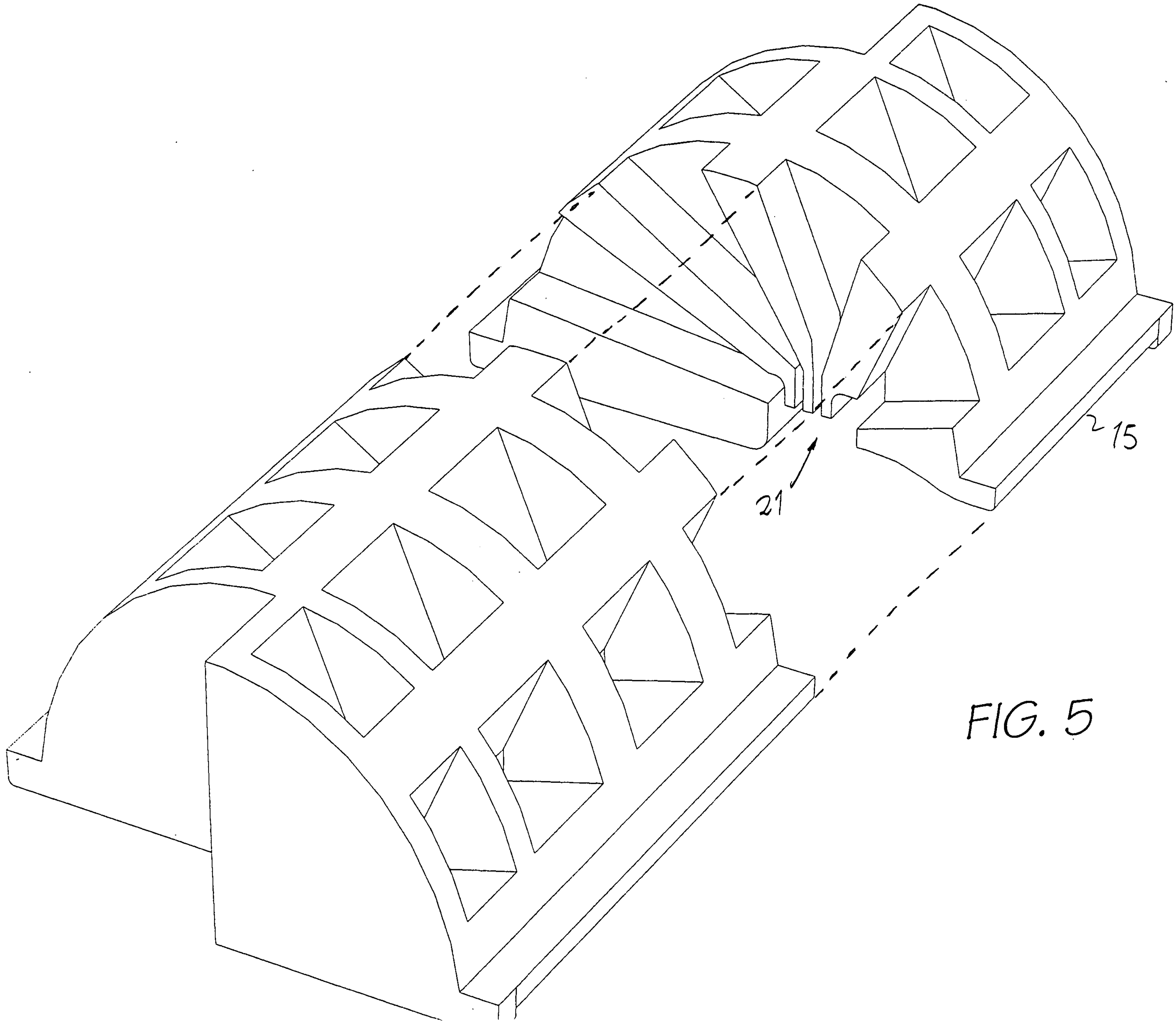


FIG. 5

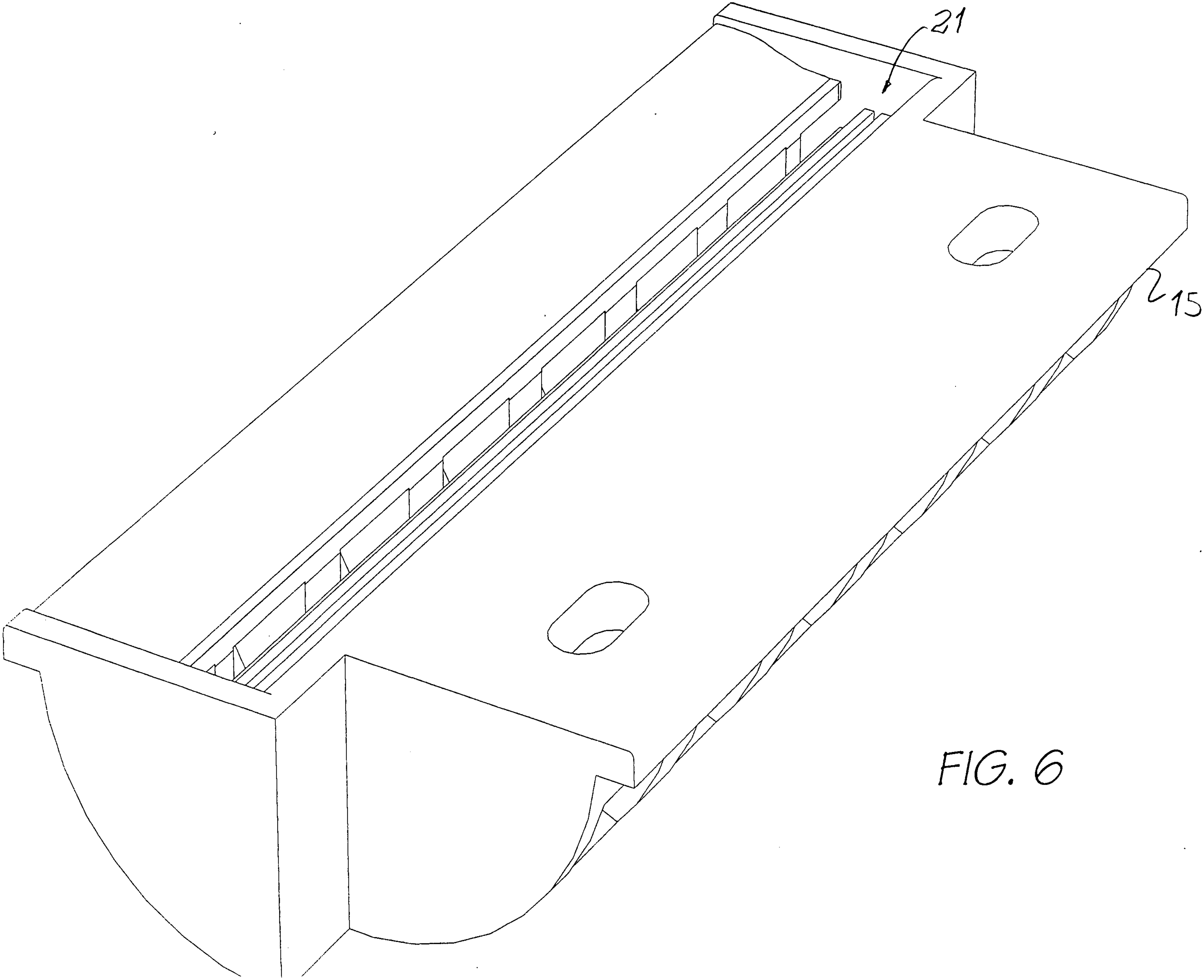


FIG. 6

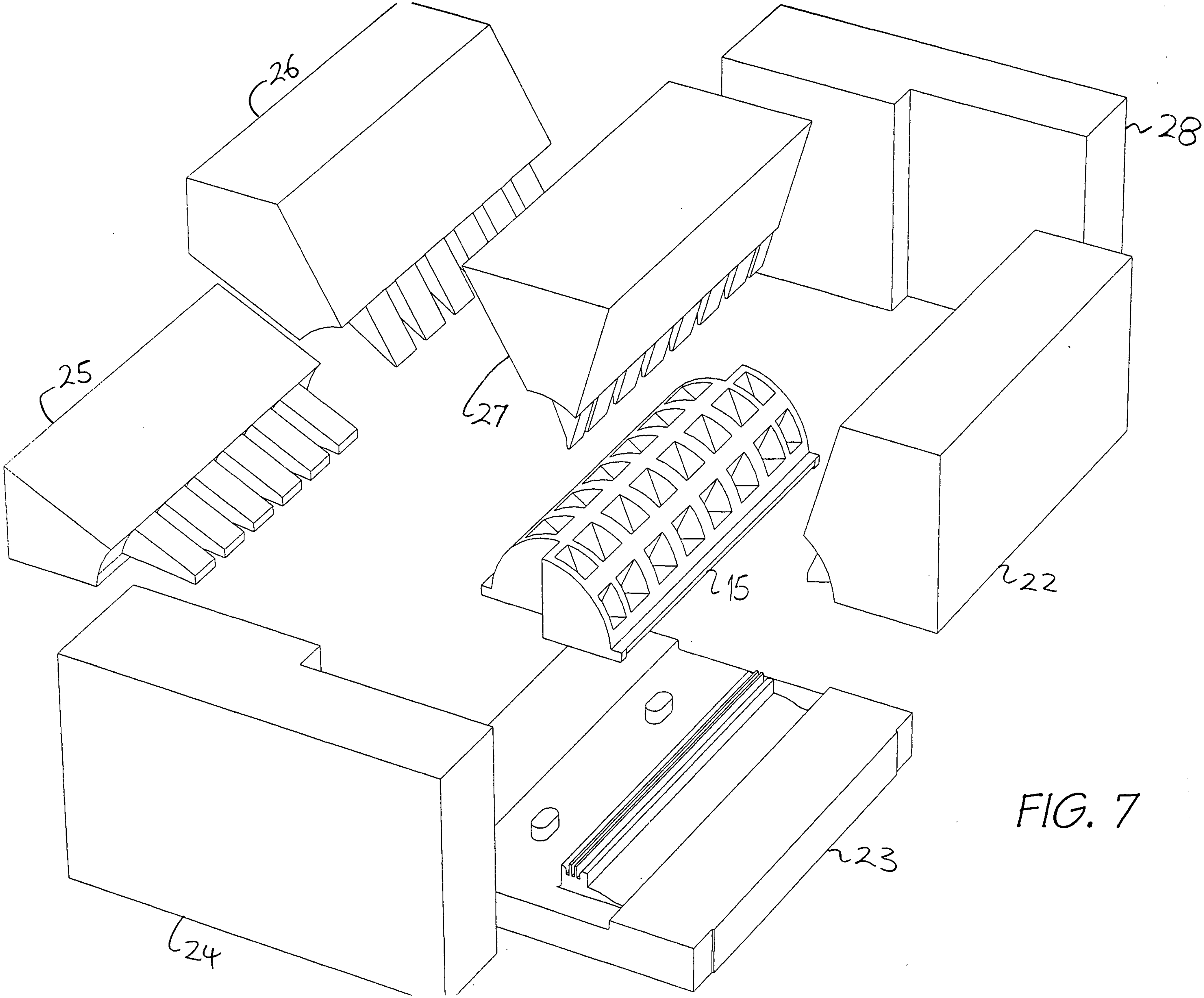


FIG. 7

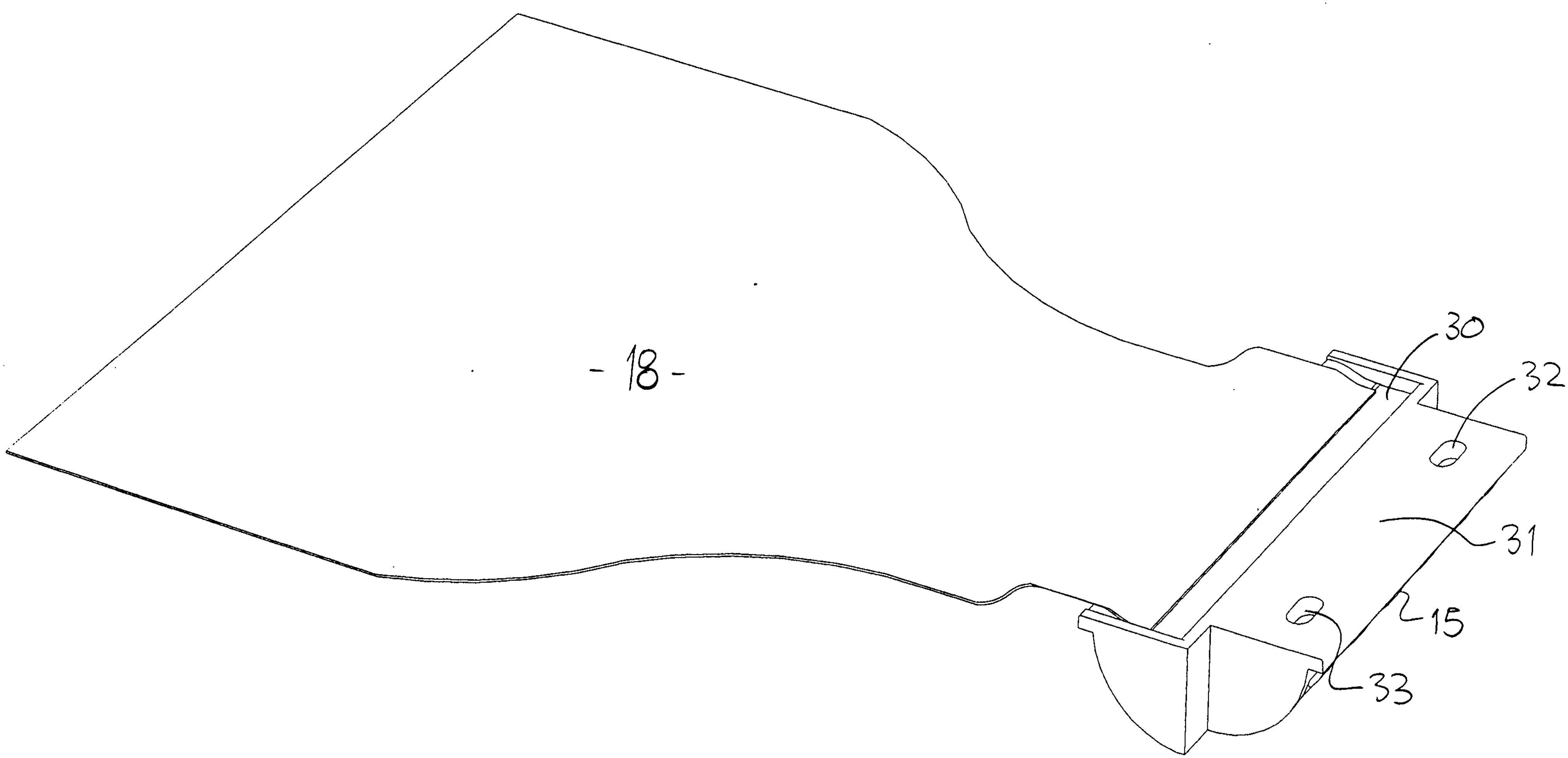


FIG. 8

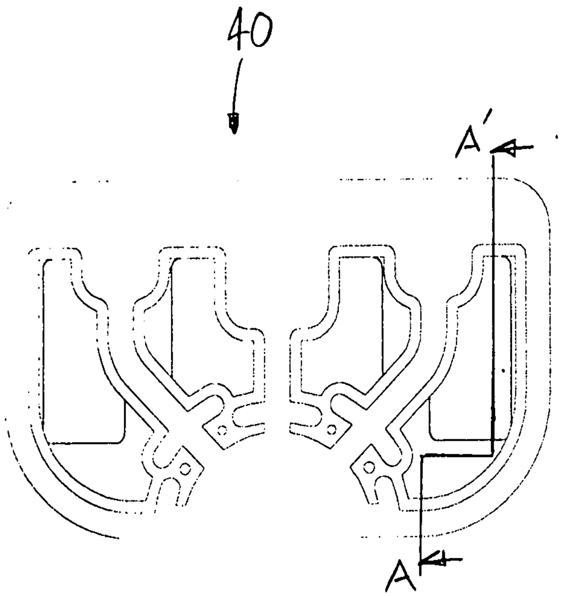
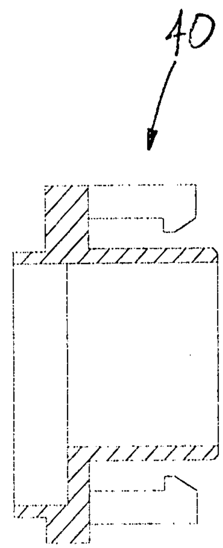


FIG. 9



A-A'
FIG. 10

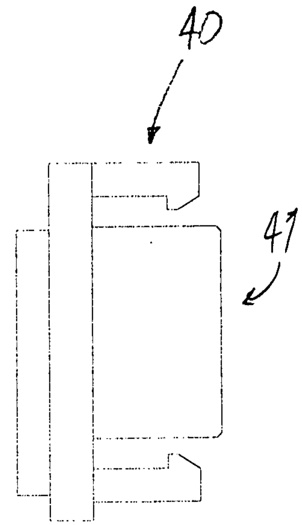


FIG. 11

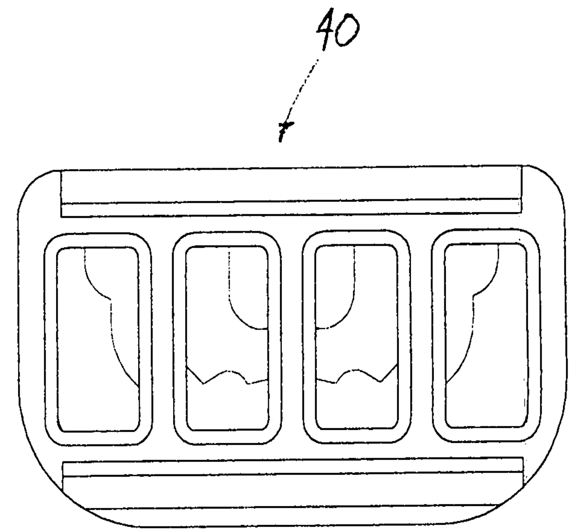


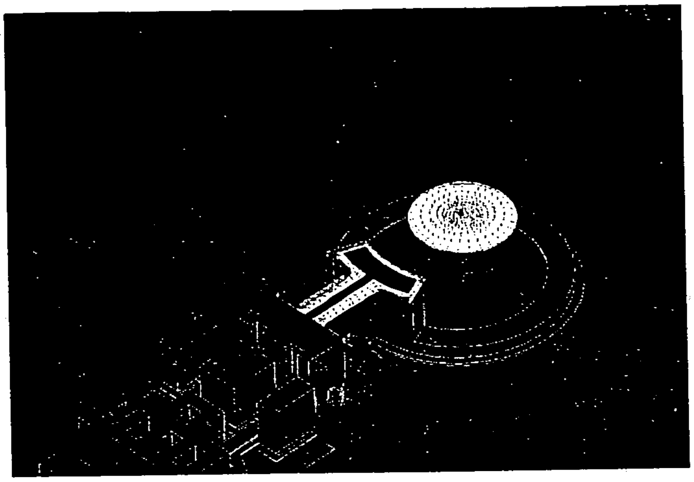
FIG. 12

ABSTRACT

A printhead carriage unit comprising: a slot for the insertion of an ink ejection printhead having a series of ink supply holes along a back surface thereof and a series of ink ejection nozzles on a front surface thereof; an abutment edge for abutment against other printhead carriage units such that the ink ejection printheads of adjacent carriage units are able to print a contiguous line. Adjacent printhead carriage units can include overlapping printhead portions such that the contiguous line can be formed from the ink ejection nozzles of either adjacent printhead. The overlap can be about 1 millimeter. The abutment edge mates with a second printhead carriage unit rotated substantially 180 degrees with respect to the first printhead carriage unit.

MEMJET

Micro Electro Mechanical Inkjet



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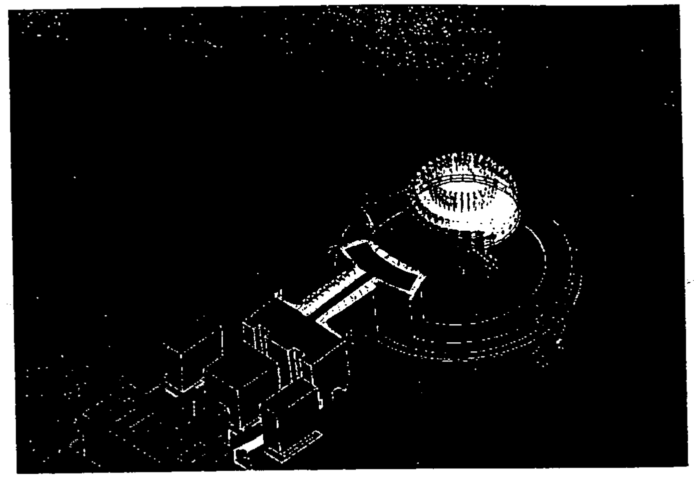

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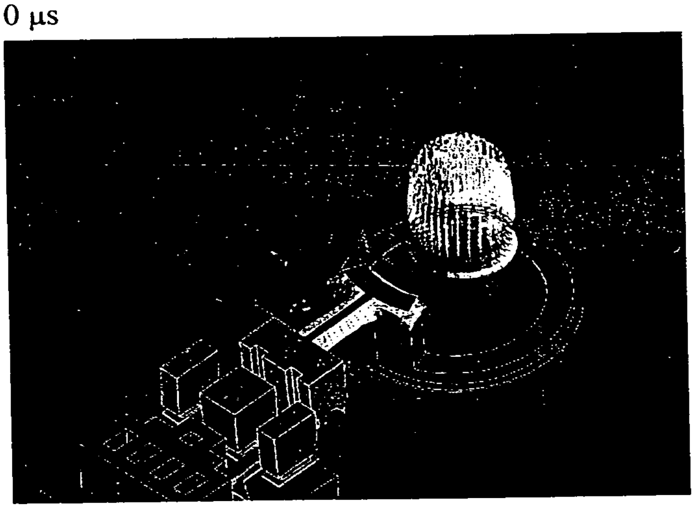

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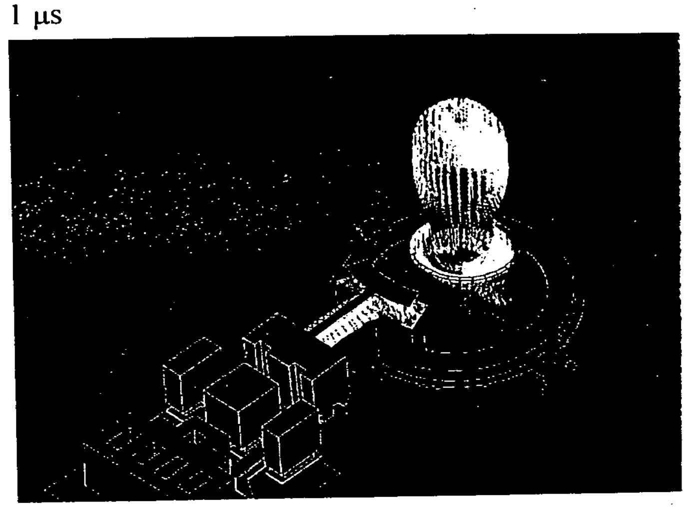

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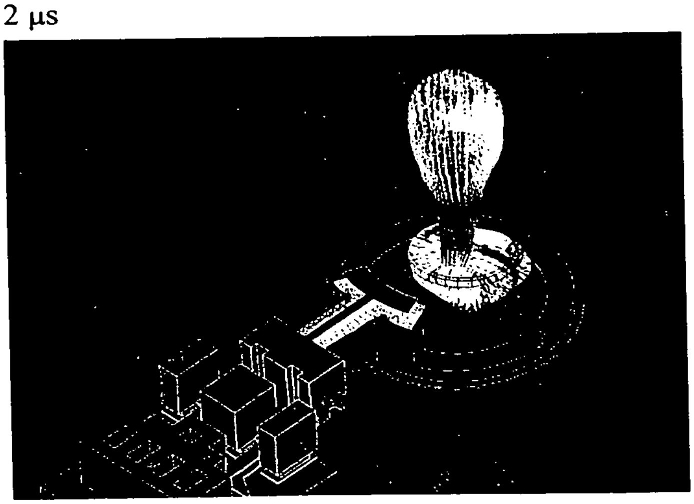

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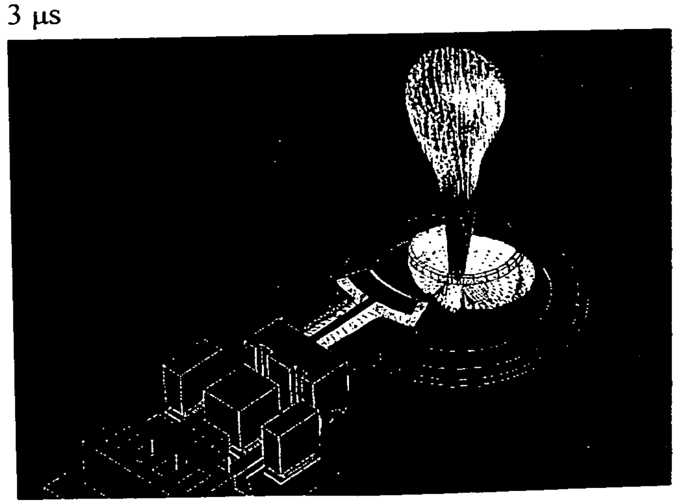

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Silverbrook Research Pty Ltd
393 Darling Street, Balmain
NSW 2041 Australia
Phone: +61 2 9818 6633
Fax: +61 2 9818 6711

Appendix A

MEMJET INTRODUCTION

Memjet is a new digital printing technology under development at Silverbrook Research. It is a 'clean slate' development aimed at developing the 'perfect' print technology for a wide range of applications for which current digital printing technologies are inadequate. The price/performance advantage over existing technologies such as laser printers and thermal inkjet printers is around two orders of magnitude.

Key Features of Memjet:

- Pagewidth inkjet printing - no scanning printheads, therefore very fast.
- High nozzle count: 51,200 nozzles for A4/letter.
- Full quality color photographic images at 1600 dpi.
- Full quality text, including Japanese Kanji.
- Wide ink and paper flexibility - three times less water than 600 dpi printers.
- High speed - 30 pages per minute (ppm) to 4000 ppm.
- High nozzle density - 25,600 nozzles in a 75mm^2 chip (compare to latest HP - 300 nozzles in 75 mm^2).
- Low cost - under $10 for a 30 ppm letter/A4 full color 1600 dpi printhead.
- Low power allows battery operation for many applications.
- Small size - printers incorporated in mobile phones, cameras, even pens.
- Simple drive circuits - 3V digital ASIC with low pincount.
- High volume manufacture - 56 million 8" heads from a 25,000 wafer per month fab.
- Low manufacturing investment -can adapt a 0.5 micron CMOS fab.
- Excellent patent protection - 220 US patents pending, both basic patents and strategic blocking patents.

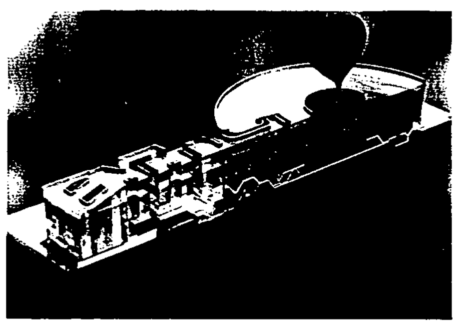
Radical, not Evolutionary

The closest technology to Memjet is Thermal Ink Jet (TIJ). This technology was invented roughly simultaneously by Canon and Hewlett-Packard around 1980 (Canon's variety is know as 'Bubblejet'), and currently results in annual revenues around $24 billion.

Thermal inkjet printheads propel a droplet of ink out of a nozzle by superheating a tiny volume of ink. This ink undergoes a flash evaporation process, forming a bubble which pushes the ink out of the nozzle.

There has been a massive investment in developing thermal inkjet technology, which has steadily advanced products from initial 200 dpi black only printers with 12 nozzles, to current full color 600 dpi printers containing printheads with as many as 608 nozzles.

However, Memjet does not use the thermal inkjet operating principle, and is not an extension of TIJ technology.



Cross section of a Memjet nozzle

Micro Electro Mechanical Systems (MEMS)

Memjet is derived from MEMS technology. MEMS is Micro Electro Mechanical Systems, and is basically the construction of mechanical systems using VLSI chip fabrication techniques. MEMS allows the integration of hundreds of millions of mechanical devices on a wafer. Certain MEMS processes (such as the Memjet process) allow the integration of MEMS and CMOS processing. This is essential for a pagewidth printhead, otherwise around 50,000 off-chip connections would be required, making the cost prohibitive for volume markets.

MEMS devices are used in many applications, though few of these applications have reached substantial volume sales. Some of the best known are

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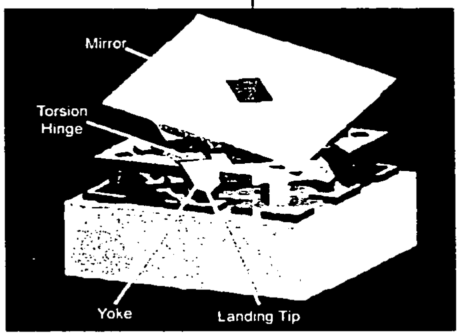
Silverbrook Research
393 Darling Street
Balmain NSW 2041
Australia
Ph: +61 2 9818 6633
Fax: +61 2 9818 6711
info@silverbrook.com.au

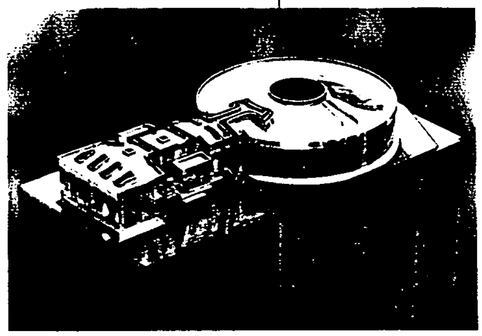
accelerometers for car airbags, and Texas Instruments' DMD (Digital Micromirror Device).

The DMD is an array of around 1 million tiny mirrors on a CMOS chip. Each mirror is independently deflected in response to video image data distributed on the CMOS chip. Each mirror reflects light either towards a viewing screen, or towards a baffle. As all of the mirrors are independently controlled, a large amount of data can be projected even though the individual speed of the mirrors is only around 50 kHz.

Memjet is conceptually similar. A Memjet printhead contains around 25,000 tiny paddles on a CMOS chip. Each paddle is independently deflected in response to page image data distributed on the CMOS chip. When deflected, each paddle pushes a microscopic ink drop out of a nozzle towards the paper. As all of the paddles are independently controlled, a large amount of data can be printed even though the individual speed of the paddles is only around 40 kHz.



Texas Instruments Digital Micromirror Device


Memjet Inkjet nozzle

Memjet Value Proposition

The value proposition of Memjet is 'practical pagewidth inkjet printing'.

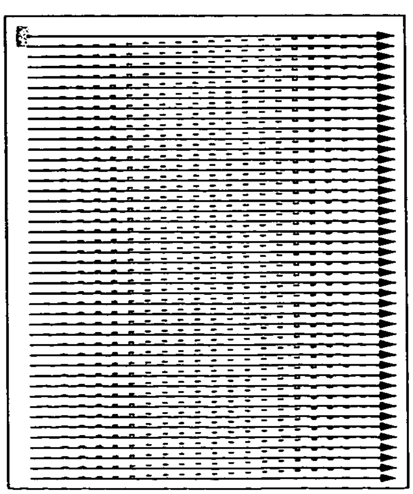
A scanning printhead is fundamentally around 100 times slower than a pagewidth printhead. This is because the a scanning printhead must scan across the page numerous times - around 40 times for draft mode and 200 times for photo quality.

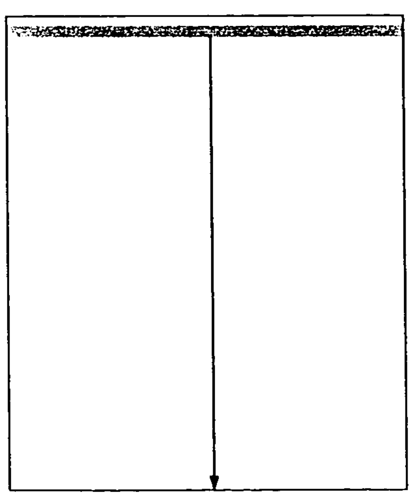
The most fundamental difference between scanning and pagewidth printheads is the width of the printhead.

There is an essential divide between scanning printheads (roughly 1/2") and pagewidth printheads (8" for US letter/A4). Printheads between these values are not very useful - there is no 'evolutionary' progression.

For example: you can't make a letter/A4 pagewidth printer out of a single 4" printhead. Neither can you make a reasonable scanning printer - a 4" print swath is virtually impossible to 'stitch' on the paper without getting highly objectionable lines across the page.

A pagewidth printhead means lots of nozzles. For a 1600 dpi, 4 color, 8" printhead, 51,200 nozzles are required. This compares to typically 300 nozzles for TIJ, and 128 nozzles for piezoelectric inkjets (such as Epson and Tektronix).


Scanning printhead


Pagewidth printhead

Previous pagewidth printhead projects

Pagewidth printheads have long been the 'holy grail' of the inkjet industry, and have been the subject of intensive research at various large companies for more than a decade.

Previous attempts at pagewidth inkjets have mostly tried to scale up either of the two current technologies - thermal inkjet or piezoelectric inkjet. Both of these approaches fail for a number of fundamental reasons.

Why cant you make pagewidth thermal inkjet printheads?

Thermal inkjet (TIJ or Bubblejet - HP and Canon's technology) is not suitable for pagewidth printheads as the power consumption is around 100 times too high. This makes it very difficult to get sufficient power into the printhead. However, even more difficult is getting the waste heat out of the printhead without boiling the ink.

TIJ cannot be made in a monolithic process, as the nozzle plates must be around 30 microns thick to withstand the transient pressures generated by the bubble. As a result, there are extraordinary manufacturing difficulties in scaling up from small printheads to pagewidth printheads. These include differential thermal expansion (making it extremely difficult to align the nozzles at both ends of a long printhead simultaneously) and cracking of the silicon chips due to the high stresses during nozzle plate attachment.

Also, TIJ and Bubblejet printheads wear out due to kogation and cavitation (neither of these problems affect Memjet or piezoelectric printheads). While it is cost effective to frequently replace 1 cm long scanning printheads, pagewidth printheads should have a longer lifetime.

Why cant you make pagewidth piezoelectric inkjet printheads?

The problems with scaling piezoelectric printheads are entirely different than those for TIJ. The main problem is acoustic crosstalk. As the printhead length increases, the delay between the acoustic pulse of a piezo actuator and its acoustic reflections from the ends of the printhead increase. This causes the pulse to interfere with itself on a timescale which reaches into the critical time of

drop ejection. Also, as the number of nozzles increases, the number of possible interference combinations undergoes a combinatorial explosion. This makes it essentially impossible to obtain consistent drop ejection at various places on the printhead.

Another problem is cost. Silicon is not a piezoelectric material, and it is extremely difficult to integrate piezoelectric materials on CMOS chips. This means that a separate external connection is required for each nozzle. A printhead equivalent to an 8" Memjet printhead would require at least 51,201 external connections. While theoretically possible, the cost of these connections is exorbitant.

The drive voltage required is around 100 V to 200 V, so it is also difficult to integrate large numbers of drivers on a single chip.

Another problem preventing integration is that the piezoelectric material must be electrically poled at around 100,000 Volts, which makes it extremely difficult to protect integrated CMOS circuitry.

How fast can a Memjet printer go?

For most consumer and PC printer applications, the full speed of Memjet is not required. In these applications, the print speed will generally be limited by the low cost paper movement mechanism.

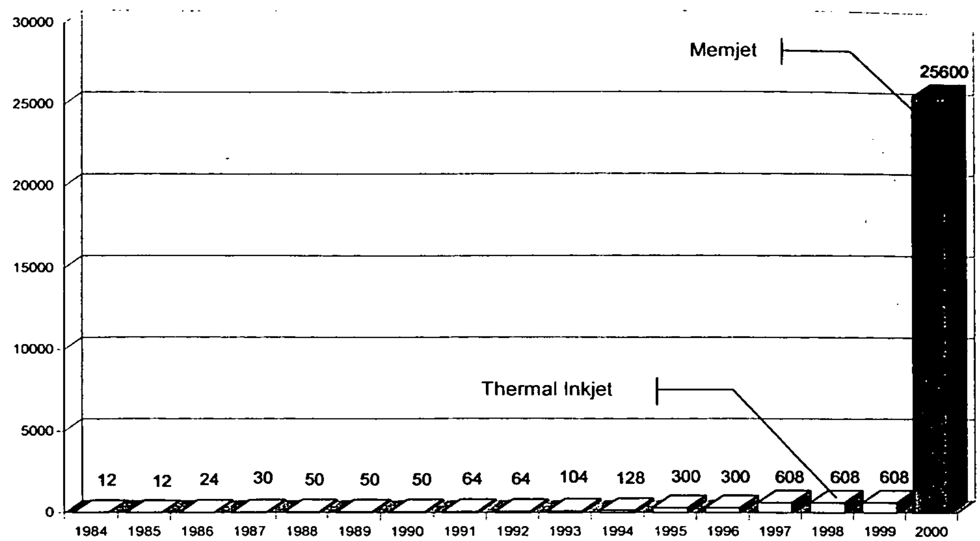
However, for various industrial and commercial printing applications, higher print speeds are desirable.

Individual Memjet nozzles can operate at 40 kHz (and are likely to operate up to 100 kHz). At 1600 dpi, this means a print speed of 25 inches per second. A 'standard' Memjet printhead has four channels for four ink colors. If this printhead is used to print a single color instead, then the maximum print speed is 100 inches per second. A 34 inch wide web (paper roll) fed printer, with printheads on both sides of the paper, printing at 100 inches per second, has an equivalent print speed of 4,364 ppm. At these print speeds, it is possible to compete directly with commercial offset printing.

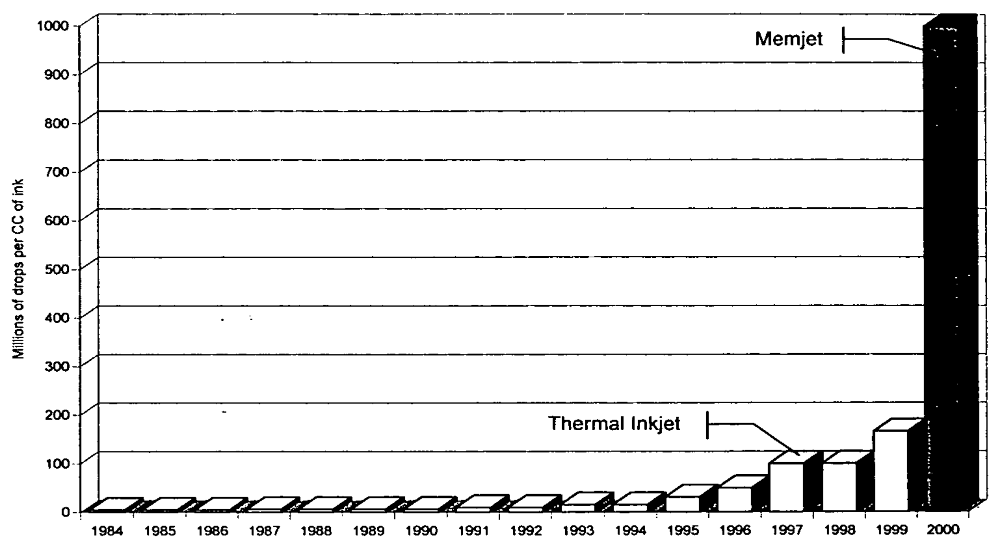
M mjet - TIJ trends

The bar charts to the right show the trends for thermal inkjet printheads from the first commercial products to the present. These trends are compared to what is expected to be the first Memjet printhead - a 4", 4 color, 1600 dpi printhead with 25,600 nozzles. Two such printhead chips butted together make up an 8" pagewidth printhead.

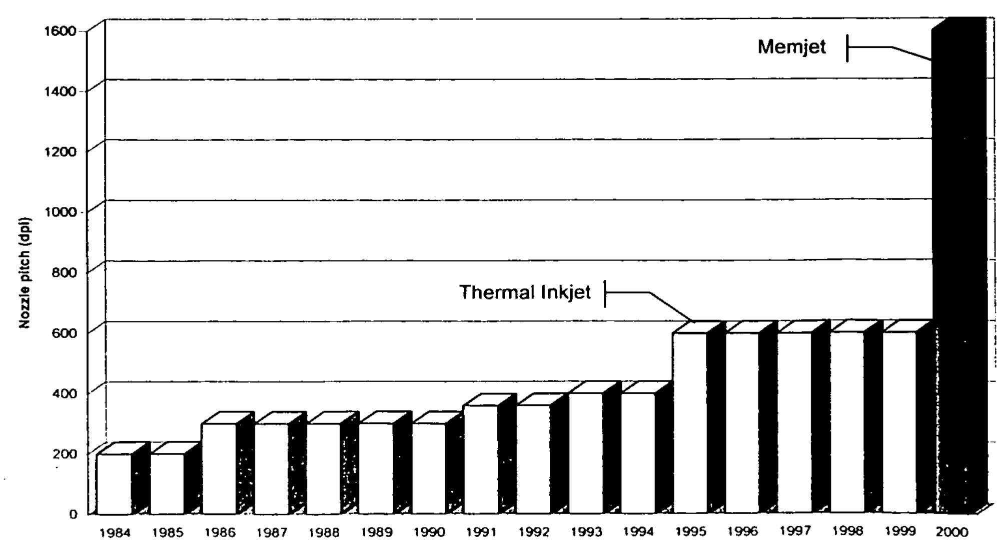
Nozzles per monolithic printhead



Ink drops per CC



Nozzle pitch



ADVANTAGES

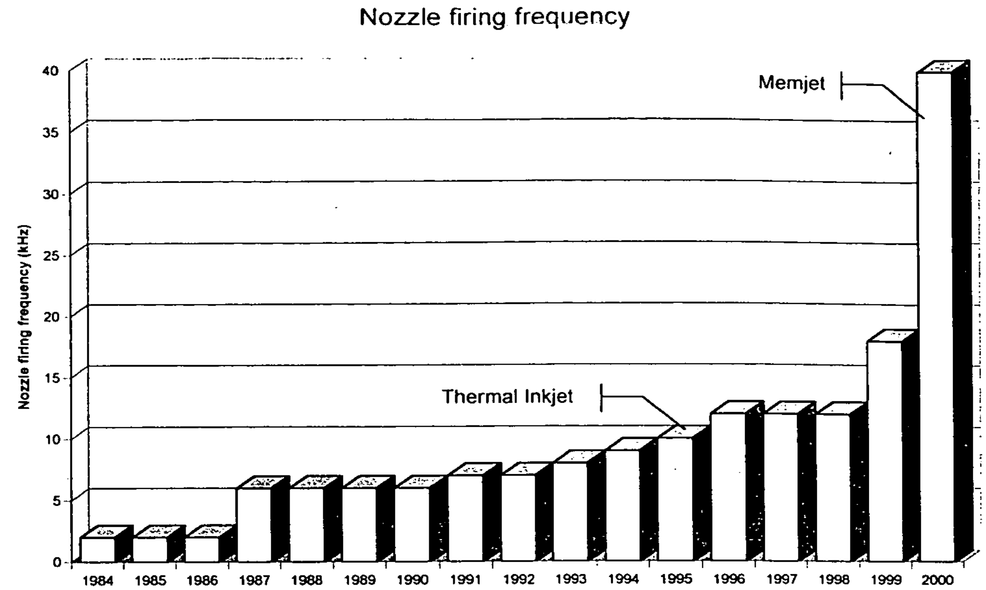
The list of advantages is long, and there are no disadvantages listed. This is because Silverbrook Research has spent years analyzing the problems with previous technologies, and ensuring that these problems are solved for Memjet. Memjet has been through 47 major design iterations to converge on its current state, where we believe that further improvements will not be significant. This quest for perfection is ongoing, and it is our intention to correct any undiscovered problems as quickly as possible. As is well known, a problem detected at an early stage can be orders of magnitude cheaper to correct than a problem detected at a prototype or production stage.

High Resolution

The true resolution of Memjet is 1600 dots per inch (dpi) in both directions. This allows full photographic quality color images, and high quality text (including Kanji). Higher resolutions are possible with the technology. 2400 dpi and 4800 dpi versions have been investigated for special applications, but 1600 dpi is chosen as ideal for most applications. The true resolution of commercially available advanced thermal inkjet devices is around 600 dpi. For piezoelectric systems such as those from Epson the true resolution is substantially lower, but the printhead makes many overlapping passes over each point giving an 'effective resolution' of 1440 dpi, at the expense of speed. 'Addressable resolution' is now often quoted in advertising to give the illusion of higher resolution.

Excellent Image Quality

High image quality requires high resolution and accurate placement of drops. The monolithic pagewidth nature of Memjet allows drop placement to sub-micron precision. High accuracy is also achieved by eliminating misdirected drops, electrostatic deflection, air turbulence, and eddies, and maintaining highly consistent drop volume and velocity. Image quality is also ensured by the provision of sufficient resolution to avoid requiring multiple ink densities. Five color or 6 color 'photo' inkjet systems introduce halftoning artifacts in mid tones (such as fleshtones) if the dye interaction and drop sizes are not absolutely perfect. This problem is eliminated in bi-level three color systems such as Memjet.

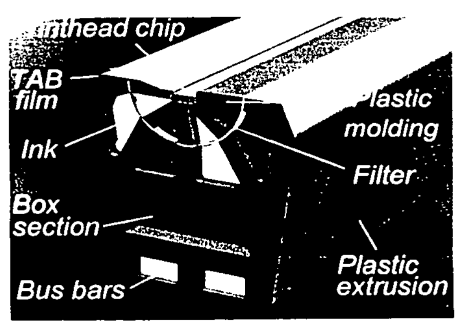


High Speed - up to 120 ppm per printhead

The pagewidth nature of the printhead allows high-speed operation, as no scanning is required. The print speed of a Memjet based printer will usually be determined by market requirements and the paper handling mechanisms required. For most consumer or SOHO applications, 30 ppm printing is around the optimum, as faster printers are dominated by complex and expensive paper handling. To achieve 30 ppm, the Memjet printhead is operated at a drop repetition rate of 10 kHz. The maximum drop repetition rate for Memjet is 40 kHz, allowing 120 ppm full color printing from a single printhead.

Low Cost

A photo-width photographic printhead assembly is projected to cost under $5, and a pagewidth A4 printhead assembly (using two 4" printhead equivalents) is projected to cost less than $10 when manufactured using a 0.5 micron CMOS process on 8" wafers.



When early 300 mm fabs eventually become cost effective, monolithic 8" printheads can be fabricated on a single wafer, reducing production costs further.

All Digital Operation

The high resolution of the printhead is chosen to allow fully digital operation using digital halftoning. This eliminates color non-linearity (a problem with continuous tone printers), and simplifies the design of drive ASICs.

Small Drop Volume

To achieve true 1,600 dpi resolution, a small drop volume is required. Memjet's drop volume is one picoliter (1 pl). The drop size of advanced commercial piezoelectric and thermal inkjet devices is around 10 to 30 pl. This has been steadily reduced over the previous two decades from original drop volumes of around 100 pl. A small drop volume also allows substantially less ink carrier (typically water) to be printed to the page, allowing much faster drying and eliminating print-through. It is theoretically possible to build a 1600 dpi thermal inkjet printhead with 1 pl drops. However, such a printhead would need to print 7.11 times as many drops as a current 600 dpi printer. It would be 7 times slower, and use around 4 times the energy, as a 600 dpi printhead with an equivalent number of nozzles. Thermal inkjet printers are already too slow and use too much power, so it is unlikely that such print-heads will be built. Memjet uses around 100 times less energy to print a drop, and uses around 100 times as many nozzles (51,200 versus around 512 for thermal inkjet), so there are no speed or power problems arising from the high resolution.

Accurate Control of Drop Velocity

As the drop ejector is a precise mechanical mechanism, and does not rely on bubble nucleation, accurate drop velocity control is available. This allows low drop velocities (4 m/s) to be used in applications where media and airflow can be controlled. Drop velocity can be accurately varied over a considerable range by varying the energy provided to the actuator. High drop velocities (10 to 15 m/s) suitable for printing on rough or fibrous surfaces (such as 'plain paper') can be achieved using variations of the nozzle chamber and actuator dimensions. Twelve meters per second is chosen as the nominal velocity for Memjet plain paper applications where airflow is uncontrolled.

Fast Drying

A combination of very high resolution, very small drops, and high dye density allows full color printing with much less water ejected. Memjet ejects around one third of the water of a 600 dpi thermal inkjet printer. This allows fast drying and virtually eliminates paper cockle.

Wide Temperature Range

Memjet is designed to cancel the effect of ambient temperature. Only the change in ink characteristics with temperature affects operation and this can be electronically compensated. Operating temperature range is expected to be 0 °C to 50 °C for water based inks.

No Special Manufacturing Equipment Required

The manufacturing process for Memjet leverages entirely from the established semiconductor manufacturing industry. Most inkjet systems encounter major difficulty and expense in moving from the laboratory to production, as high accuracy specialized manufacturing equipment is required. For Memjet, the equipment required has already been developed at a cost of many billions of dollars for the semiconductor industry.

High Production Capacity Available

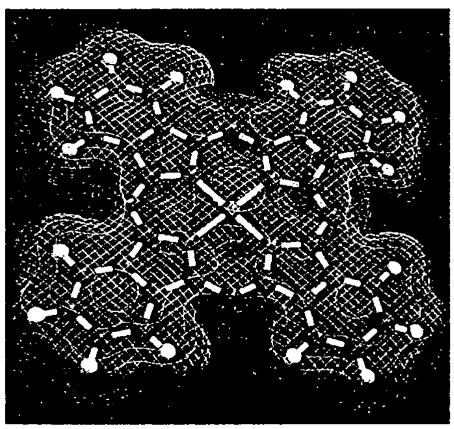
An 8" CMOS fab with 25,000 wafer starts per month can produce around 56 million 8" printheads per annum. There are currently many such CMOS fabs in the world.

Low Factory Setup Cost

The factory set-up cost is low because existing 0.5 micron 6" and 8" CMOS fabs can be used. At the time of projected introduction of the printheads these fabs should be fully amortized, and essentially obsolete for CMOS logic production. Therefore, volume production can use 'old' existing facilities. Most of the MEMS post-processing can also be performed in a CMOS fab, but at least one new piece of equipment will be required, - a deep silicon etcher using the 'Bosch process'. These machines are available from Alcatel, PlasmaTherm, and Surface Technology Systems.

Good Light- Fastness

As the ink is not heated, there are few restrictions on the types of dyes that can be used. This allows dyes to be chosen for optimum light-fastness. Some recently developed dyes from companies such as Zeneca Specialties and BASF have light-fastness of 7 on the blue wool scale. This is equal to the light-fastness of many pigments, and considerably in excess of photographic dyes and of early inkjet dyes.



Copper phthalocyanine - a blue chromophore - showing an electron density isosurface mapped with electric potential

Good Water- Fastness

As with light-fastness, the lack of thermal restrictions on the dye allows selection of dyes for characteristics such as water-fastness. For extremely high water-fastness (as is required for washable fabrics) reactive dyes can be used.

Excellent Color Gamut

The use of transparent dyes of high color purity allows a color gamut considerably wider than that of offset printing and silver halide photography. Offset printing in particular has a restricted gamut due to light scattering from the pigments used. With three-color systems (CMY) or four-color systems (CMYK) the gamut is necessarily limited to the tetrahedral volume between the color vertices. Therefore it is important that the cyan, magenta and yellow dyes are as spectrally pure as possible. A slightly wider 'hexcone' gamut that includes pure reds, greens, and blues can be achieved using a 6 color (CMYRGB) model. Such a six-color printhead can be made economically with a width of only 1 mm.

Elimination of Color Bleed

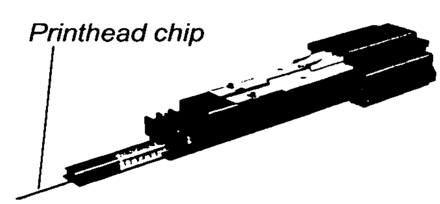
Ink bleed between colors occurs if the different primary colors are printed while the previous color is wet. While image blurring due to ink bleed is typically insignificant at 1600 dpi, ink bleed can 'muddy' the midtones of an image. Ink bleed can be eliminated by using microemulsion-based ink, for which Memjet is highly suited. The use of microemulsion ink can also help prevent nozzle clogging and ensure long-term ink stability.

Advanced Ink Formulations

Silverbrook Research has world-class expertize in quantum chemistry (refer to papers in J. Phys. Chem. and Chemical Physics Letters), and is applying this to the development of a new class of inks with advanced properties.

High Nozzle Count

Memjet has 19,200 nozzles in a monolithic CMY three-color photographic printhead. While this is large compared to other printheads, it is a small number compared to the number of devices routinely integrated on CMOS VLSI chips in high volume production. It is also less than 3% of the number of movable mirrors which Texas Instruments integrates in its Digital Micromirror Device (DMD), manufactured using similar CMOS + MEMS processes.



Cutaway of packaged photographic printhead

51,200 Nozzles per A4 Pagewidth Printhead

A four-color (CMYK) Memjet printhead for pagewidth letter/A4 printing uses two chips. Each 0.65 cm^2 chip has 25,600 nozzles for a total of 51,200 nozzles.

Integration of Drive Circuits

In a printhead with as many as 51,200 nozzles, it is essential to integrate data distribution circuits (shift registers), data timing, and drive transistors with the nozzles. Otherwise, a minimum of 51,201 external connections would be required. This is a severe problem with piezoelectric inkjets, as drive circuits cannot be integrated on piezoelectric substrates. Integration of many millions of connections is common in CMOS VLSI chips, which are fabricated in high volume at high yield. It is the number of off-chip connections that must be limited.

Monolithic Fabrication

Memjet is made as a single monolithic CMOS chip, so no precision assembly is required. All fabrication is performed using standard CMOS VLSI and MEMS processes and materials.

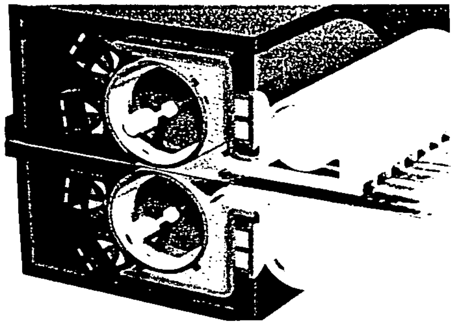
In thermal inkjet and some piezoelectric inkjet systems, the assembly of nozzle plates with the printhead chip is a major cause of low yields, limited resolution, and limited size. Also, pagewidth arrays are typically constructed from multiple smaller chips. The assembly and alignment of these chips is an expensive process.

Modular, Extendable for Wide Print Widths

Long pagewidth printheads can be constructed by butting 'standard' 100 mm Memjet heads together. The edge of the Memjet printhead chip is designed to automatically align to adjacent chips. One printhead gives a photographic size printer, two gives an A4 printer, and four gives an A3 printer. Larger numbers can be used for high speed digital printing, pagewidth wide format printing, and fabric printing.

Low Cost Simultaneous Double Sided Printing

Double sided printing (known as 'duplex' in the office market, and 'perfect' in the commercial print market) can be implemented at low cost simply by including an extra printhead on the other side of the paper, and duplicating the appropriate logic and image processing circuits. The cost and complexity of providing two printheads is less than that of mechanical systems to turn over the sheet of paper.



Simultaneous duplex printhead assembly

Straight Paper Path

As there are no drums required, a straight paper path can be used to reduce the possibility of paper jams. This is especially relevant for office duplex printers, where the complex mechanisms required to turn over the pages are a major source of paper jams.

High Efficiency

Thermal inkjet printheads are only around 0.1% efficient (electrical energy input compared to drop kinetic energy and increased surface energy). Memjet is more than 10 times as efficient.

Self-Cooling Operation

The energy required to eject each drop is 142 nJ (0.142 microJoules), a small fraction of that required for thermal inkjet printers. The low energy allows the printhead to be completely cooled by the ejected ink, with only a 32 °C worst-case ink temperature rise. No heat sinking is required.

Low Pressure

The maximum pressure generated in a Memjet printhead is around 60 kPa (0.6 atmospheres). The pressures generated by bubble nucleation and collapse in thermal inkjet and bubblejet systems are typically in excess of 10 MPa (100 atmospheres), which is 160 times the maximum Memjet pressure. The high pressures in bubblejet and thermal inkjet designs result in high mechanical stresses.

Low Power

A 30 ppm A4 Memjet printhead requires a maximum of 67 Watts when printing full 3-color black. When printing 5% coverage, average power consumption is only 3.4 Watts.

Low Voltage Operation

Memjet can operate from a single 3V supply, the same as typical drive ASICs. Thermal inkjets typically require at least 20 V, and piezoelectric inkjets often require more than 50 V. The Memjet actuator is designed for nominal operation at 2.8 volts, allowing a 0.2 V drop across the drive transistor, to achieve 3V chip operation.

Operation from 2 or 4 AA Batteries

Power consumption is low enough that a photographic Memjet printhead can operate from AA batteries. A typical 6 x 4 inch photograph requires less than 20 Joules to print (including drive transistor losses). Four AA batteries are recommended if the photo is to be printed in 2 seconds. If the print time is increased to 4 seconds, 2 AA batteries can be used.

Battery Voltage Compensation

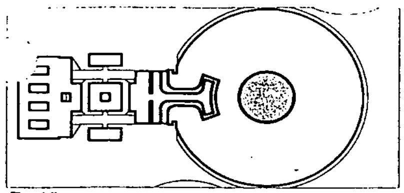
Memjet can operate from an unregulated battery supply, to eliminate efficiency losses of a voltage regulator. This means that consistent performance must be achieved over a considerable range of supply voltages. Memjet senses the supply voltage, and adjusts actuator operation to achieve consistent drop volume.

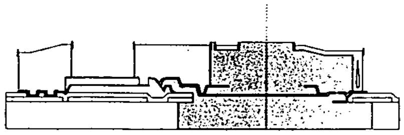
Advanced Nozzle Clearing

Memjet employs two novel patented techniques to clear clogged nozzles, and most conventional techniques can also be used. The degree of potential nozzle clogging is highly dependent on the ink formulation, which depends on the application. In photographic applications clog-proof inks can be used. Hot melt inks can also be completely clog free. When using aqueous inks, it is essential to use nozzle capping and to include a humectant in the ink.

Small Actuator and Nozzle Area

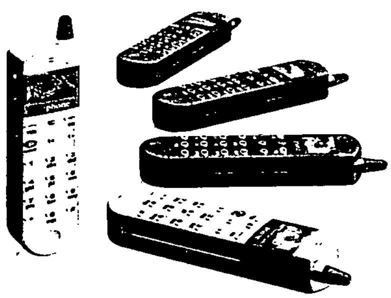
The area required by a Memjet nozzle, actuator, and drive circuit is 3200 μm^2. This is much less than 1% of the area required by piezoelectric inkjet nozzles, and around 1.5% of the area required by TIJ nozzles. The actuator area directly affects the printhead manufacturing cost.





Small Total Printhead Size

An entire printhead assembly (including ink supply channels) for a letter/A4, 30 ppm, 1600 dpi, four color printhead is 210 x 12 x 10 mm. The small size allows incorporation into notebook computers and miniature printers. A photograph printer is 106 x 8 x 8 mm, allowing inclusion in pocket digital cameras, palmtop PCs, mobile phone/fax, and so on. Ink supply channels take most of this volume. The photographic printhead chip itself is only 102 x 0.55 x 0.3 mm.



Printers in 3G mobile phones

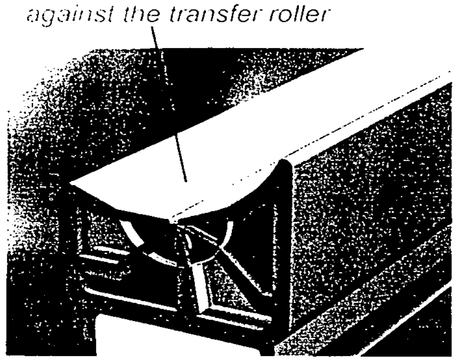
Various Nozzle Capping Systems

Nozzle capping systems have been designed for various applications.

A miniature nozzle capping system has been designed for portable and photographic applications. For a photographic printer this nozzle capping system is only 106 x 5 x 4 mm, and does not require the printhead to move.

For very low cost printers, such as printers incorporated into pens, the nozzle capping mechanism is a single piece of molded plastic costing less than a cent.

In desktop printers, the printhead can be capped against a transfer roller for robust operation and consumer-proofing.



Cross section of packaged printhead (CEprint version)

High Manufacturing Yield

The projected manufacturing yield (at maturity) of the Memjet printheads is at least 80%, as it is primarily a 0.5 micron digital CMOS chip with an area of only 0.15 cm^2 per inch of printhead. Most modern CMOS processes achieve high yield with chip areas in excess of 1 cm^2. For chips less than around 1 cm^2, cost is roughly proportional to chip area. Cost increases rapidly between 1 cm^2 and 4 cm^2, with chips larger than this rarely being practical. There is a strong incentive to ensure that the chip area is less than 1 cm^2.

For thermal inkjet and bubblejet printheads, the chip width is typically around 5 mm, limiting the cost effective chip length to 1 to 2 cm. A major target of Memjet has been to reduce the chip width as much as possible, allowing cost effective monolithic pagewidth printheads.

In the early stages of manufacture, before high yields are obtained, fault tolerance can be used. Although fault tolerance doubles the 'raw' chip area, wafers with defect densities as high as 100 defects per cm^2 can still obtain good printhead yields.

Low Process Complexity

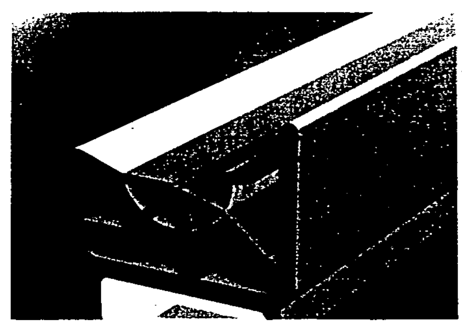
With digital IC manufacture, the mask complexity of the device has little or no effect on the manufacturing cost or difficulty. Cost is proportional to the number of process steps, and the lithographic critical dimensions. Memjet uses a standard 0.5 micron 1P2M CMOS manufacturing process, with an additional 7 MEMS mask steps. This makes the manufacturing process less complex than a typical 0.25 micron CMOS logic process with 5 level metal. However, as the MEMS postprocessing is not standard, a significant amount of process development is required. Considerable effort has been undertaken to minimize the complexity and risk of this process development. However, since any process development is usually difficult and expensive, this is likely to be the highest portion of the remaining development costs.

Simple Testing

Memjet includes test circuits and a test strategy that allows most testing to be completed at the wafer probe stage. Testing of all electrical properties, including the resistance of the actuator, can be completed at this stage. However, actuator motion can only be tested after release from the sacrificial materials. Actuators can be tested before being filled with ink using optical methods. The paddle is reflective and the nozzle chamber is transparent. Paddle deflection can be measured accurately by counting interference fringes of monochromatic light. Final testing of packaged printheads is readily performed by printing a test pattern which is automatically checked using a linear image sensor.

Low Cost Packaging

Memjet is packaged in an injection molded polycarbonate package. All connections are made using Tape Automated Bonding (TAB) technology, though wire bonding can be used as an option. All connections are along one edge of the chip.



Molded plastic package

Relaxed Critical Dimensions

The critical dimension (CD) of the Memjet CMOS drive circuitry is 0.5 microns. Advanced digital ICs such as microprocessors currently use CDs of around 0.25 microns, which is two device generations more advanced than the Memjet printhead requires. Most of the MEMS post processing steps have CDs of 1 micron or greater.

Low Stress during Manufacture

Devices cracking during manufacture are a critical problem with both thermal inkjet and piezoelectric devices. This limits the size of the printhead that it is possible to manufacture. The stresses involved in the manufacture of Memjet printheads are no greater than those required for CMOS fabrication. Memjet printheads are not sawn from the wafer, but are gently plasma etched instead.

No Scan Banding

Memjet is a full pagewidth printhead, so does not scan. This eliminates one of the most significant image quality problems of inkjet printers. Banding due to other causes (mis-directed drops, printhead misalignment) is usually a significant problem in pagewidth printheads. These causes of banding have also been addressed.

'Perfect' Nozzle Alignment

All of the nozzles within a printhead are aligned to sub-micron accuracy by the 0.5 micron stepper used for the lithography of the printhead. Nozzle alignment of two 4" printheads to make an A4 pagewidth printhead is achieved with the aid of mechanical alignment features on the printhead chips. This allows automated mechanical alignment (by simply pushing two printhead chips together) to within 1 micron. If finer alignment is required in specialized applications, 4" printheads can be aligned optically.

Controllable Drop Velocity

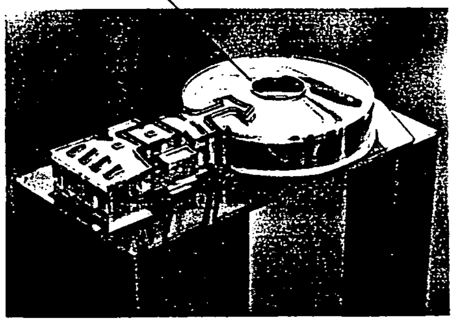
An accurately controlled drop velocity improves image quality, as the position of dots on the moving substrate is more accurate. An accurate drop velocity also enables a lower nominal drop velocity, which reduces power consumption. A low drop velocity requires laminar airflow, with no eddies, to achieve good drop placement on the print medium. This is achieved by the design of the printhead packaging.

For printing on 'rough' surfaces higher drop velocities are desirable. Drop velocities up to 15 m/s can be achieved using variations of the design dimensions. It is possible to manufacture printheads with a 4 m/s drop velocity, and printheads with a 15 m/s drop velocity, on the same wafer. This is because both can be made using the same process parameters.

No Misdirected Drops

Misdirected drops are eliminated by the provision of a thin rim around the nozzle, which prevents the spread of a drop across the printhead surface in regions where the hydrophobic coating is compromised.

Nozzle rim



No Thermal Crosstalk

When adjacent actuators are energized in bubblejet or other thermal inkjet systems, the heat from one actuator spreads to others, and affects their firing characteristics. In Memjet, heat diffusing from one actuator to adjacent actuators affects both the heater layer and the bend-canceling layer equally, so has no effect on the paddle position. This virtually eliminates thermal crosstalk.

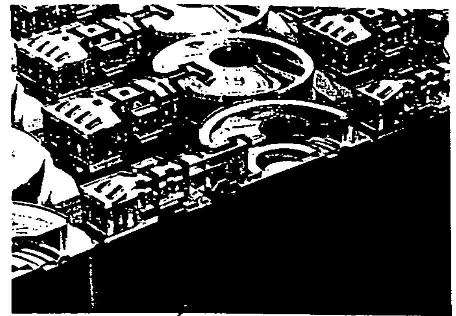
No Structural Acoustic Crosstalk

This is a major problem with piezoelectric printheads. It does not occur in Memjet.

No Fluidic Acoustic Crosstalk

Each simultaneously fired nozzle is at the end of a 300 micron long ink inlet etched through the (thinned) wafer. These ink inlets are connected to large ink channels with low fluidic resistance. This configuration virtually eliminates any effect of drop ejection from one nozzle on other nozzles.

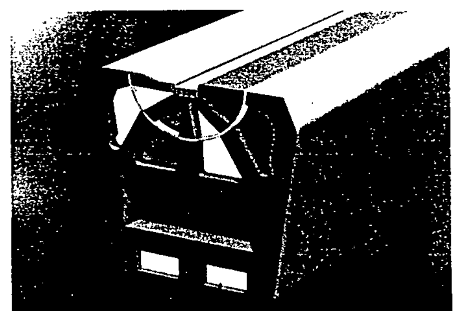
Acoustic crosstalk between 'pods' (groups of nozzles sharing an ink channel) is almost entirely eliminated by the 300 micron long channels opening into relatively large fluid reservoirs. Acoustic crosstalk within a pod is effectively eliminated by the time delay between subsequent drop ejections within a pod. This is typically 20 microseconds, which is more than 40 times longer than the resonant frequency of the ink channel. This gives plenty of time for acoustic vibrations to be damped between drop ejections.



Ink channel

No Power Supply Crosstalk

The thick copper bus-bars in the device package, and the active power supply compensation mechanism, effectively eliminate crosstalk coupled through the power supply.



Bus bars

Permanent Printhead

All of the known problems that limit the life of inkjet printheads have been eliminated, allowing the printheads to be permanently installed. This dramatically lowers the production cost of consumables. Note, however, that the selling price of consumables is not necessarily related to the production cost, and need not be reduced.

No Kogation

Kogation (residues of burnt ink, solvent, and impurities, from the Japanese 'koga' for burnt rice) is a significant problem with bubblejet and other thermal inkjet printheads. Memjet does not have this problem, as the ink is not heated.

No Cavitation

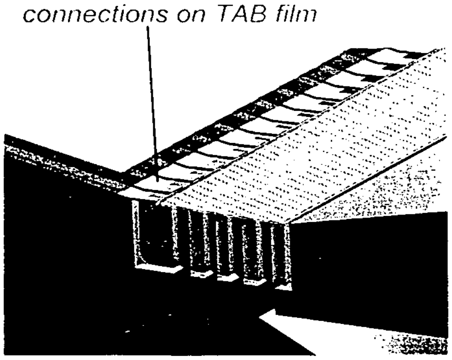
Erosion caused by the violent collapse of bubbles is another problem that limits the life of bubblejet and other thermal inkjet printheads. Memjet does not have this problem because no bubbles are formed.

No Electromigration

No metals are used in Memjet actuators or nozzles, which are entirely ceramic. Therefore, there is no problem with electromigration in the actual inkjet devices. The CMOS metallization layers are designed to support the required currents without electromigration. This can be readily achieved because the current considerations arise from heater drive power, not high speed CMOS switching.

Distributed Power Connections

While the energy consumption of Memjet is fifty times less than thermal inkjet, the high print speed and low voltage results in a fairly high electrical current consumption. Worst case current for a photographic Memjet head printing in two seconds from a 3 Volt supply is 4.9 Amps. This is supplied via copper busbars to 256 bond pads along the edge of the chip. Each bond pad carries a maximum of 40 mA. On chip contacts and vias to the drive transistors carry a peak current of 1.5 mA for 1.2 μs, and a maximum average of 12 mA.



Close-up cross section of packaged printhead

No Corrosion

The nozzle and actuator are entirely formed of glass and titanium nitride (TiN), a conductive ceramic commonly used for metallization barrier layers in CMOS devices. Both materials are at minimum chemical energy levels with respect to water, so do not corrode. Titanium nitride does not corrode or dissolve in extreme environments such as molten aluminum. It is used as the coating for the electrodes in aluminum smelters. TiN is also highly wear resistant - many watches and jewelry items are coated with TiN as it looks like gold, but has much better wear properties.

TiN does slowly oxidize in air above 500 °C, which limits the efficiency of the actuator, as the actuator efficiency is proportional to its temperature rise. Greater efficiency can be obtained by the use of (Ti,Al)N, which has similar properties to TiN but resists oxidation up to 900 °C.

No Electrolysis

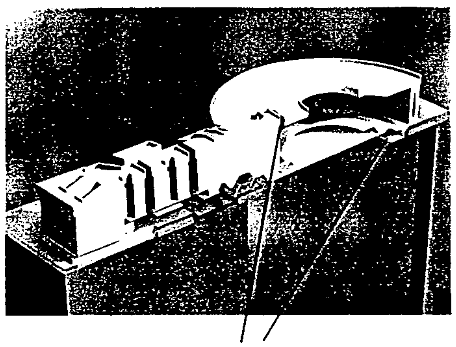
The ink is not in contact with any electrical potentials, so there is no electrolysis. This is achieved by a deliberate design feature in the actuator arm, which is a gap between the actuator loop and the paddle. This electrically isolates the paddle from the drive circuit.

No Fatigue

All actuator movement is within elastic limits, and the materials used are all ceramics, so there is no fatigue. Finite element analysis shows the maximum strain to be 0.5%.

No Friction

No moving surfaces are in contact, so there is no friction.



The actuator and paddle do not contact the nozzle chamber.

No Stiction

'Stiction' is a combination of 'sticking' and 'friction', a problem common to many MEMS devices. Memjet is designed to eliminate stiction during the release of the actuators. This is achieved by the low ratio of width to thickness of the cantilever beam, in combination with the high Young's modulus of the TiN layers.

No Crack Propagation

Finite element analysis (FEA) has shown the maximum strain to be 0.5%. This is well within the crack propagation limit of the actuator, with the typical surface roughness of the TiN layers.

No Electrical Poling Required

Piezoelectric materials must be poled after they are formed into the printhead structure. This poling requires very high electrical field strengths - around 20,000 V/cm. The high voltage requirement typically limits the size of piezoelectric printheads to around 5 cm, requiring 100,000 Volts to pole. Memjet requires no poling.

No Rectified Diffusion

Rectified diffusion - the formation of bubbles due to cyclic pressure variations - is a problem that primarily afflicts piezoelectric inkjets. Memjet is designed to prevent rectified diffusion, as the ink pressure never falls below zero.

Elimination of the Saw Street

The saw street between chips on a wafer is typically 200 microns. This would take 26% of the wafer area. Instead, plasma etching is used, requiring just 4% of the wafer area. This also eliminates breakage during sawing.

Lithography Using Standard Steppers

Although Memjet printhead chips can be as long as the wafer is wide, standard steppers (which typically have an imaging field around 20 mm square) are used. This is because the printhead is 'stitched' using identical half inch exposures. Alignment between stitches fields is not critical, as there are no electrical connections between stitch regions. One segment of each of 32 printheads is imaged with each stepper exposure, giving an 'average' of 4 printheads per exposure.

Integration of Full Color on a Single Chip

Memjet integrates all of the colors required onto a single chip. This cannot be done with pagewidth 'edge shooter' designs, such as Canon Bubblejet.

Wide Variety of Inks

Memjet does not rely on the ink properties for drop ejection. Inks can be based on water, microemulsions, oils, various alcohols, MEK, hot melt waxes, or other solvents. Memjet can be 'tuned' for inks over a wide range of viscosity and surface tension. This is one significant factor allowing a wide range of applications.

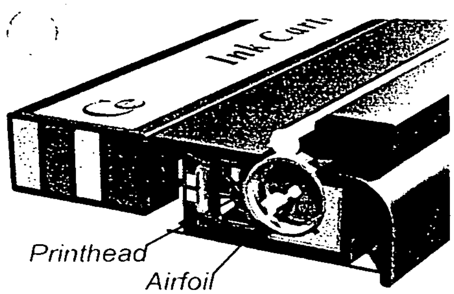
Archival Quality

With the right choice of dye and media, archival permanence significantly better than color photographs can be achieved.

Laminar Air Flow with no Eddies

The printhead packaging is designed to ensure that airflow is laminar, and to eliminate eddies. This is important, as

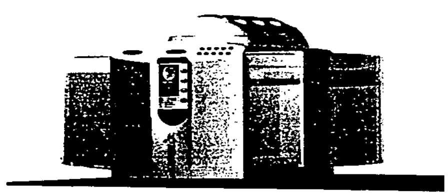
eddies or turbulence could degrade image quality due to the small drop size.



Printer with controlled airflow

High Drop Repetition Rate can be used

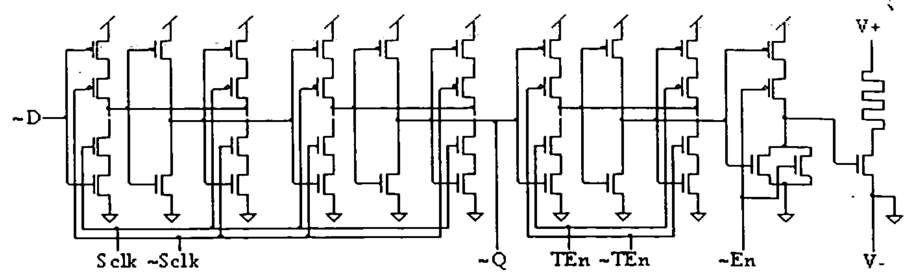
The nominal drop repetition rate of a photographic Memjet is 5 kHz, resulting in a print speed of 2 seconds per photo. The nominal drop repetition rate for an A4 printhead is 10 kHz for 30+ ppm A4 printing. The maximum drop repetition rate is primarily limited by the nozzle refill rate, which is determined by nozzle chamber geometry, flow dynamics, ink pressure, and surface tension. Drop repetition rates of 40 kHz can be achieved (and 100 kHz may be achievable), allowing print speeds of 120 ppm using a single row of nozzles for each color. However, 34 ppm is entirely adequate for most low cost consumer applications.



120 ppm duplex desktop printer

For very high-speed applications, such as commercial printing, multiple printheads can be used in conjunction with fast paper handling. A suitable system for high end commercial printing can use one printhead per color per side. On a 34 inch web, this would give an effective (A4 equivalent) print speed of 10,900 ppm with a 6.25 m/s paper speed.

If the printer speed is reduced, the energy required to print a page is distributed over a longer time, so the power consumption is reduced. For operation from AA batteries this can be important,



Per-nozzle CMOS circuit

as the internal resistance of the batteries limits the available power. The battery lifetime is not an important issue, as hundreds of pages can be printed from one set of batteries. The drop repetition rate can be reduced as low as desired to reduce power consumption, as the CMOS design is fully static.

Low Head-to-Paper Speed

The nominal head to paper speed of a photographic Memjet printhead is only 0.076 m/sec. For an A4 printhead it is only 0.16 m/sec., which is about a third of the typical scanning inkjet head speed. The low speed simplifies printer design and improves drop placement accuracy. However, this head-to-paper speed is enough for 34 ppm printing, due to the pagewidth printhead. Higher speeds can readily be obtained where required.

High Speed CMOS not Required

The clock speed of the printhead shift registers is only 14 MHz for an letter/A4 printhead operating at 30 ppm. For a photographic printer, the clock speed is only 3.84 MHz. This is much lower than the speed capability of the CMOS process used. This simplifies the CMOS design, and eliminates power dissipation problems when printing near-white images.

Fully Static CMOS Design

The shift registers and transfer registers are fully static designs. A static design requires 35 transistors per nozzle, compared to around 13 for a dynamic design. However, the static design has several advantages, including higher noise immunity, lower quiescent power consumption, and greater processing tolerances.

Wide Power Transistor

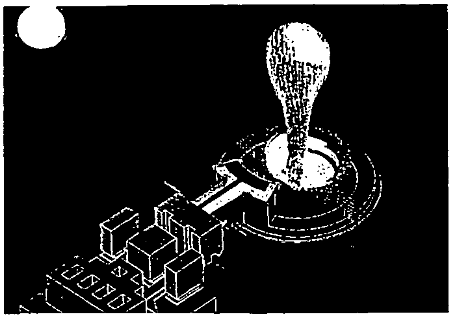
The width to length ratio of the power transistor is 688. This allows a 4 Ohm on-resistance, whereby the drive transistor consumes 6.7% of the actuator power when operating from 3V. This size transistor fits beneath the actuator. Thus an adequate drive transistor, along with the associated data distribution circuits, consumes no chip area that is not already required by the actuator.

There are several ways to reduce the percentage of power consumed by the transistor: increase the drive voltage so that the required current is less, reduce the lithography to less than 0.5 micron, use BiCMOS or other high current drive technology, or increase the chip area, allowing room for drive transistors which are not underneath the actuator. However, the 6.7% consumption of the present design is considered a cost/performance optimum.

Extensive Simulation

Extensive simulations of fluid dynamic, mechanical, thermal, electrical, and other characteristics of the device have been performed. These are done using software developed at Silverbrook Research, in combination with several leading commercial software packages (Ansys, Fidap, and Matlab). Simulation is used as a 'computational microscope' which is able to 'see' microscopic stresses, temperature profiles, and fluid flow in ways impossible with physical experiments. All simulations performed at Silverbrook Research are 'causal'. That is, no assumptions are made about the motion of the ink or other aspects of the device. A simulated voltage pulse is provided to the actuator, and then we watch what happens. Simulations are performed at sufficient resolution to capture the detailed behavior of features such as satellite drops. More than 2,000 simulations have been performed, using more than 20,000 hours

of compute time on several high performance workstations.



Simulated drop ejection of a Memjet nozzle.

YIELD

Yield is, of course, a critical aspect [illegible]anufacturing any chips. For this reason, we have put considerable emphasis on maximizing yield. The base CMOS process is 0.5 micron, a mature technology able to achieve very high yields on reasonable sized chips. The chip size is small: about 8 mm^2 per 1/2" print head segment (1.3 cm^2 for an 8" printhead).

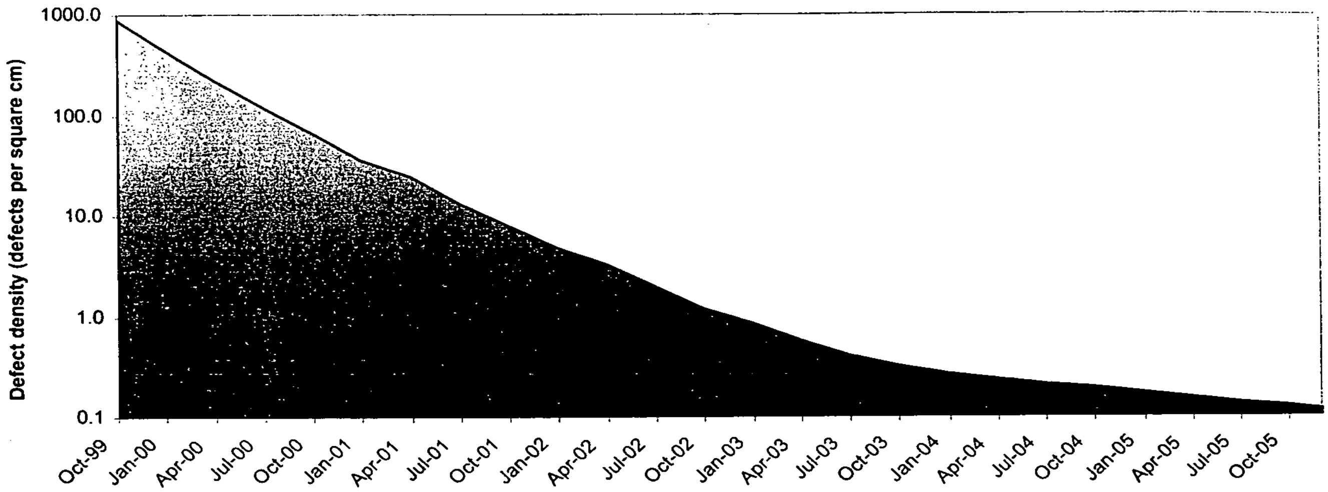
The MEMS process itself is not very sensitive to particulate contamination - most feature sizes are well above 1 micron, and most layers are quite insensitive to particulate contamination.

However, it is not a good idea to be complacent about yield, especially for a new process. Accordingly, the yield estimates that we use are pessimistic. The yield is calculated from the defect density for four different printhead configurations.

Yield ramp-up

This projection assumes a slow yield ramp-up over around 5 years. It starts with a defect density of more than 100 defects per cm^2, falling to around 0.2 per cm^2 by 2005.

Defect Density used for these financial projections (log scale)
(note: these defect density projections are intended as a worst case estimate for conservative financial projections - actual defect densities will probably be much lower)



Redundancy and Fault Tolerance

To allow cost-effective production of printheads in the early years when the defect density is high, redundant printheads can be used.

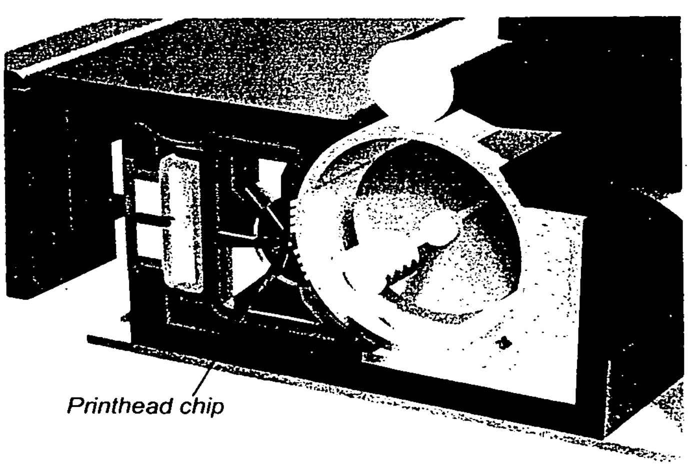
The business model automatically selects between four configurations of print-head, depending upon how the cost of each configuration changes with changing yield. These configurations are:

1) A printhead with full redundancy (two complete rows of nozzles) made from tested and matched 1/2" printhead segments (a total of 32 half inch segments).

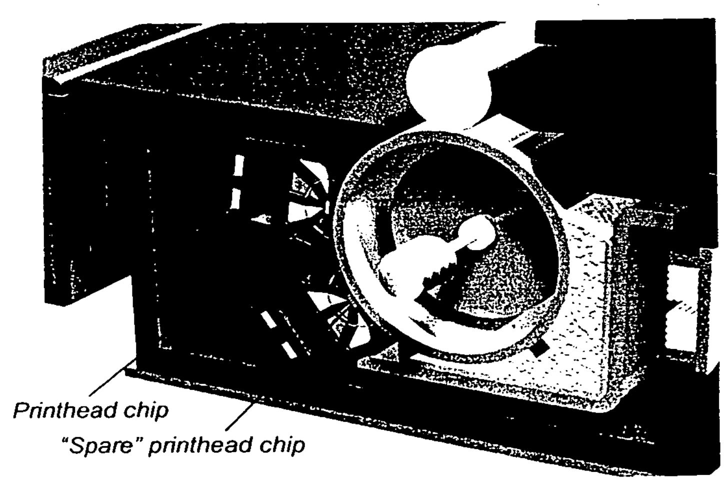
2) A printhead with full redundancy made from two rows of untested 4" printhead segments (a total of 4 four inch segments).

3) A printhead with no redundancy made from 16 half inch tested segments.

4) A printhead with no redundancy made from 2 four inch tested segments.



Normal printhead configuration with a single set of nozzles (51,200 total nozzles)

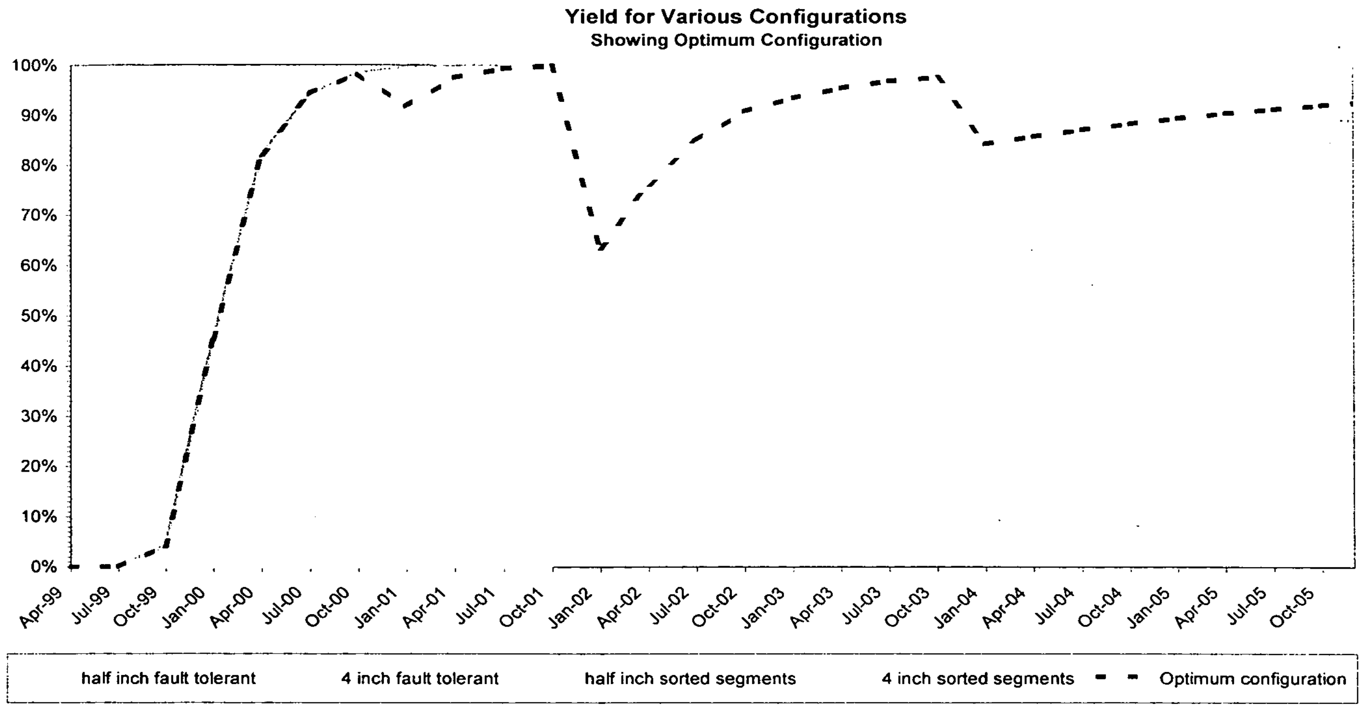


Redundant printhead configuration with two sets of nozzles (102,400 total nozzles)

Printhead Yield

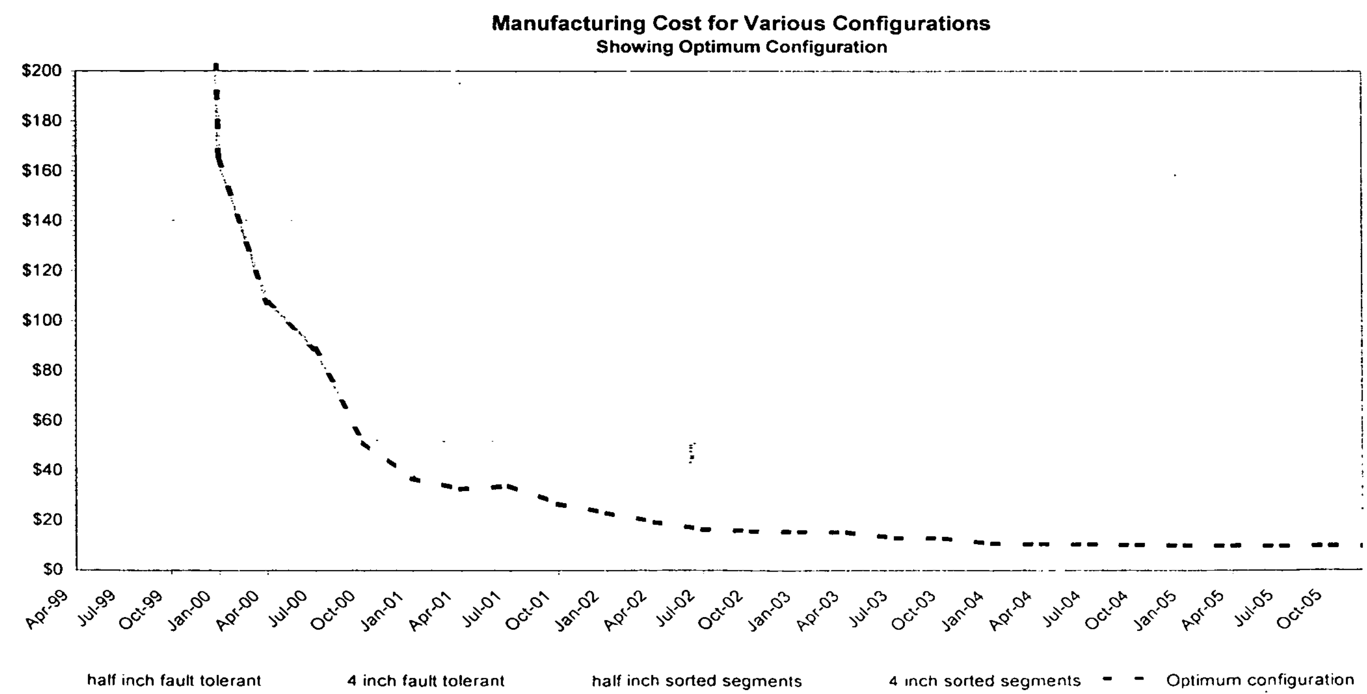
The overall printhead yield can be in- ved dramatically by the use of redundancy / fault tolerance when the defect densities are high.

The following graph shows the 'sort yield' of 8" printheads of four different types based on the defect density curve above.



Printhead Manufacturing Cost

The manufacturing cost of the printhead changes with yield. Although the yield of the fault tolerant configurations of printhead will always be higher than non-fault tolerant configurations, fault tolerance is not cost effective once the defect densities are low enough. The primary reason for this is that two complete sets of nozzles are required for fault tolerance (unlike memories, where a few redundant rows and/or columns are sufficient). The graph below reflects the total manufacturing costs of printheads, including device sorting and packaging. The volume of manufacture is also considered into the cost projection.



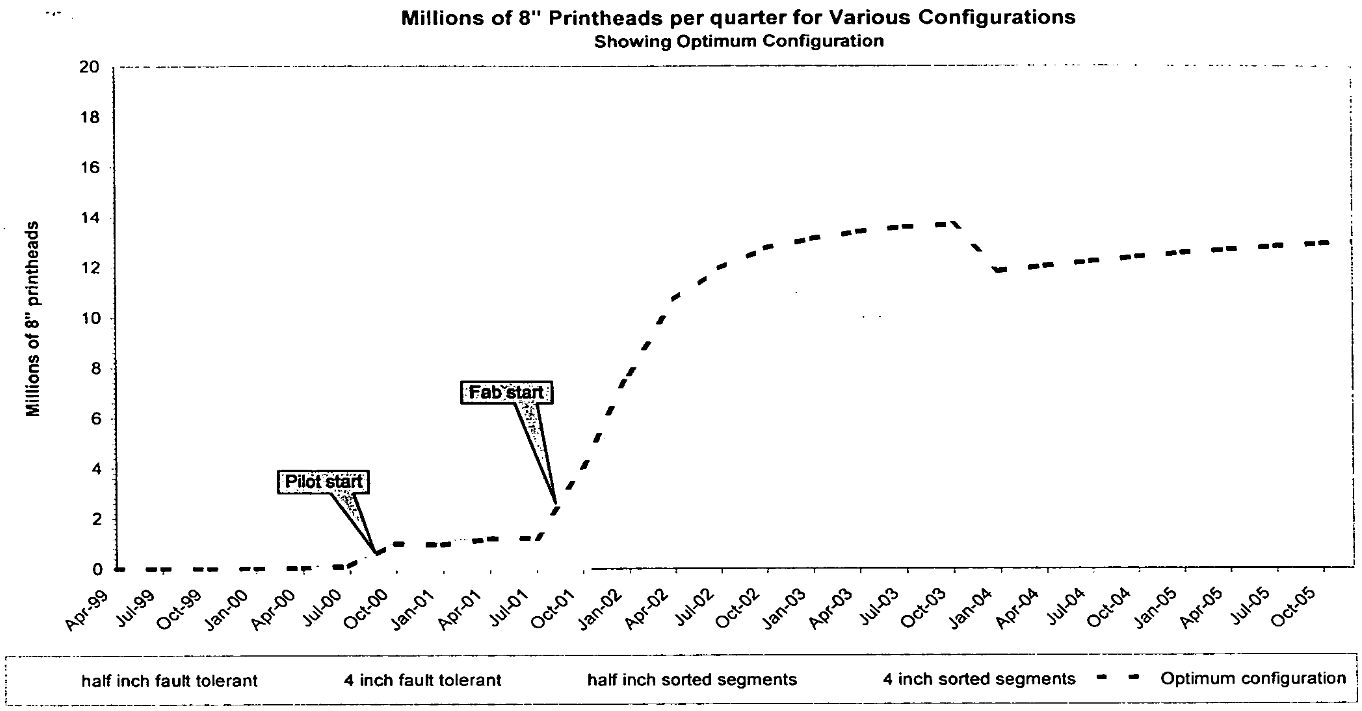
VOLUME

The manufacturing volume is pre-[illegible]d to go through three major phases:

1) An initial lab phase, where only around 100 wafers per month are processed, the yield are low to none, and the available number of printheads is very limited. Defect densities above 100 per cm^2 are assumed.

2) A pilot phase, where the number of wafers processed each month is 5,000. Defect densities are assumed to be between 10 per cm^2 and 100 per cm^2, necessitating the use of redundancy to achieve good printhead yields.

3) A full manufacturing phase, where 25,000 wafers are processed each month. Here defect densities are expected to fall from around 8 per cm^2 to 0.1 per cm^2 over the course of five years. During this phase, it is more cost effective *not* to use redundancy.



Early Product Mix

The market focus during the pilot phase and the main production phase should be different. During the pilot phase, markets which are relatively insensitive to print-head cost should be targeted. These include:

1) Wide format printing (machine prices around $10,000)

2) Network color printing (machine prices between $3,000 to $7,000)

3) Digital commercial printing (machine prices $100,000 and up)

4) Photo finishing (machine prices between $5,000 and $20,000)

During the main manufacturing phase, high volume markets can also be targeted.

Memjet Prototype Fabrication

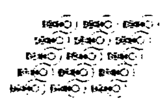
Before an integrated CMOS + MEMS prototype is made, we recommend the fabrication of a MEMS only prototype. The MEMS prototype can be made very faithfully to a full print head, with nearly identical actuator and nozzle structure. The main limitation of a MEMS only prototype is that the number of nozzles is limited, as a separate bond pad is required for each nozzle.

The prototype described here has only 15 nozzles per chip. The behavior of a few groups of 5 nozzles is a near perfect model of the entire chip performance, as the fluidic, thermal, electrical, acoustic, or mechanical coupling between 5 nozzle groups is extremely small.

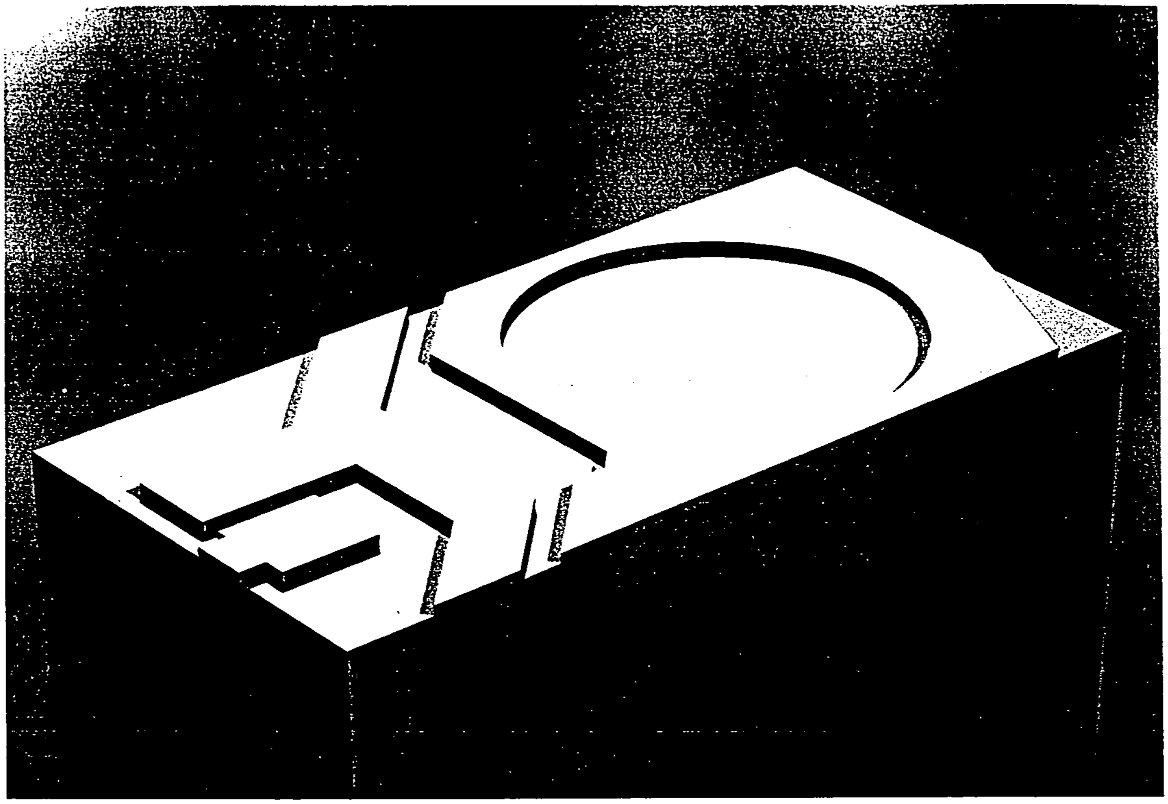
A chip layout with 15 nozzles is shown below. This chip is 3 mm x 3 mm, and is replicated on a 1.2 x 1.2 cm mask set. The mask set contains 10 variants of the precise nozzle dimensions, plus various test structures. The mask also contains a test printhead with around 3000 nozzles. As there is no CMOS on the chip, only some of the nozzles are 'wired up'. This chip is intended to test mechanical aspects of handling and packaging.

The mask has been laid out using 'Tanner Tools', and is available as Tanner or GDSII files.

The subsequent pages show the process steps, and the mask for a single nozzle unit cell.



1) 1 Micron Aluminum

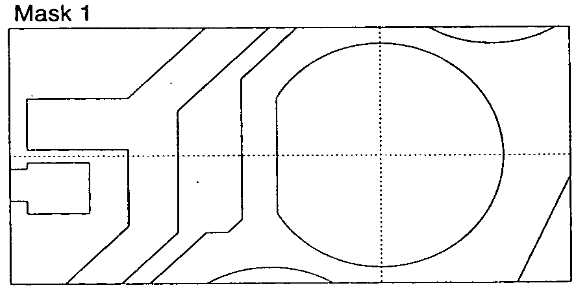


PROCESS DETAILS

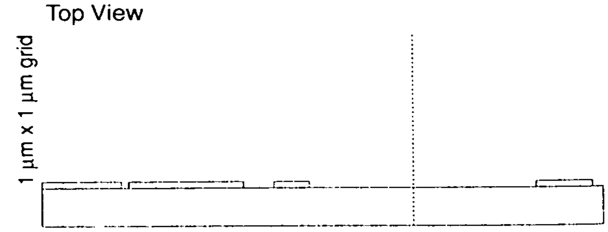
One micron of aluminum is deposited and etched using Mask 1. This mask includes the electrodes to the actuator, the bond pads, and the wiring between these items. It is possible to replace the aluminum with TiN wiring and bond pads. However, that would diverge further from the CMOS + MEMS design, and add process risks. The region around the nozzle chamber is on Metal1 for a 1P2M CMOS + MEMS process, while the electrodes are on metal 2.

Layer thickness	1 micron (nominal)
Thickness variation	± 50%
Linewidth	3 microns
CD Accuracy	± 0.2 microns
Alignment accuracy	Mechanical
Align to	Wafer flat
Production process	CMOS M1 and M2
Production mask	Contains wiring

Mask 1

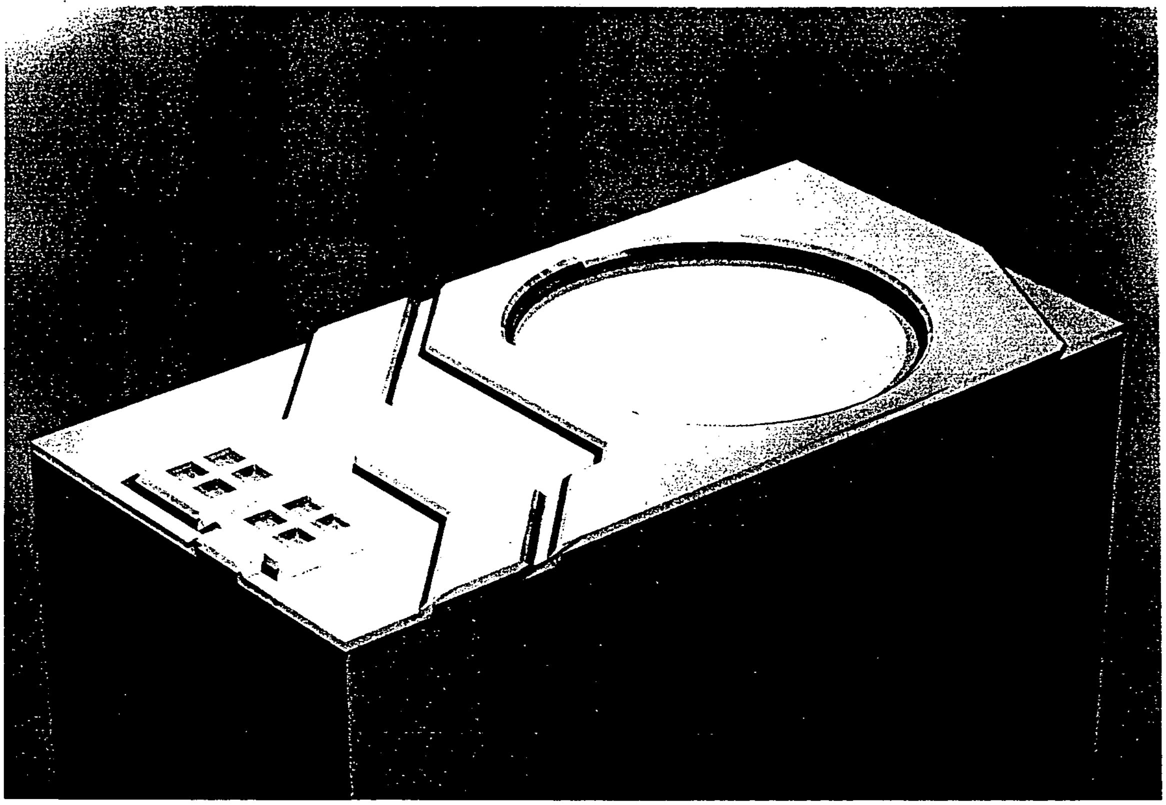


Top View



Deposit and etch 1 micron aluminum

2) 1 Micron PECVD Nitride

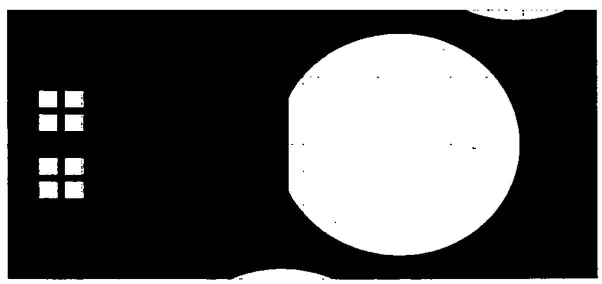


PROCESS DETAILS

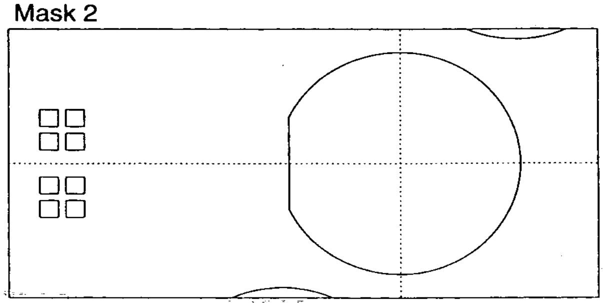
One micron of PECVD silicon nitride is deposited and etched using Mask 2. This mask includes the vias from the aluminum to the first TiN layer, and some relatively minor fluid control aspects. For a CMOS + MEMS process, this is the passivation layer, and will typically be 0.5 microns of glass followed by 0.5 microns of silicon nitride.

A pure nitride passivation layer is preferable, to prevent ions from the ink from diffusing through the glass.

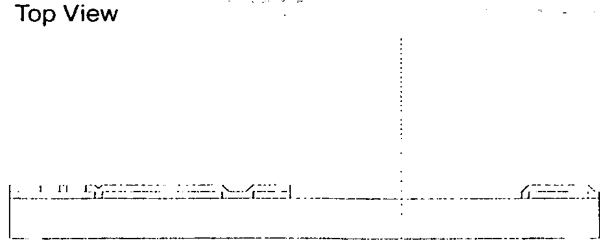
Layer thickness	1 micron
Thickness variation	± 20%
Linewidth	1 micron
CD Accuracy	± 0.2 microns
Alignment accuracy	± 0.2 microns
Align to	Metal 1
Production process	CMOS passivation
Production mask	Same



Mask 2

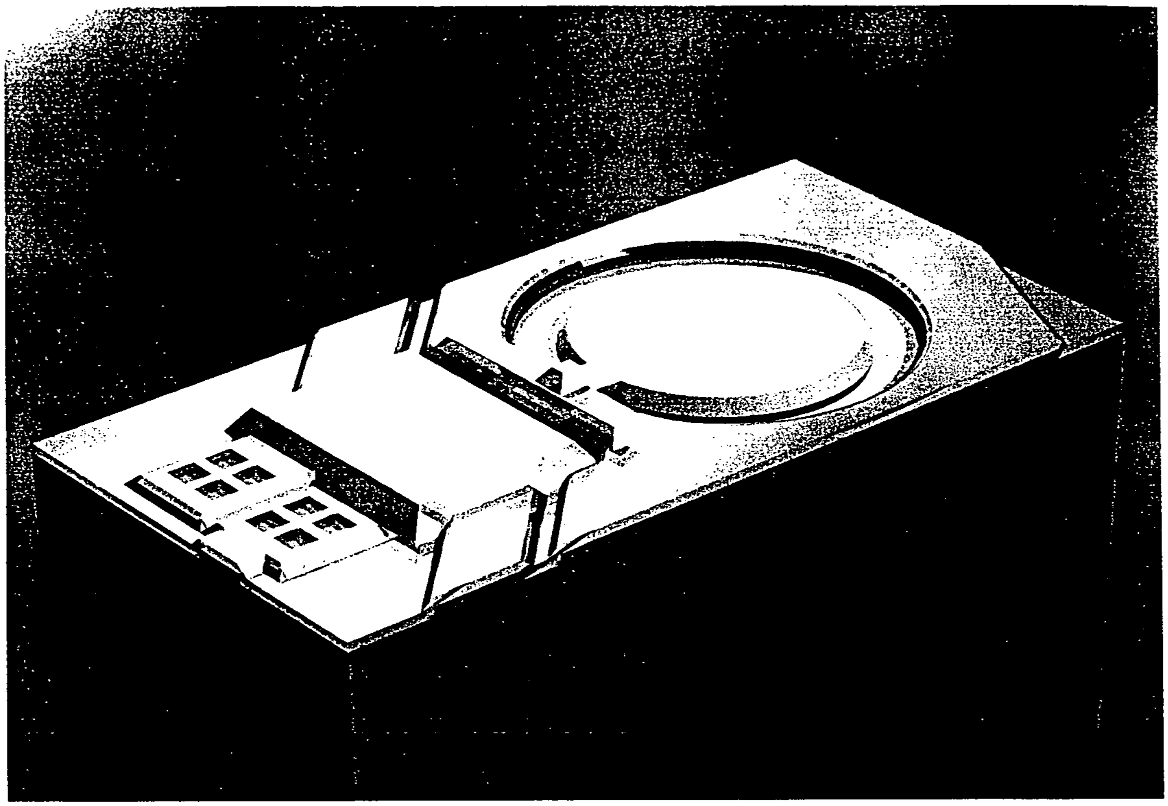


Top View



Deposit and etch 1micron PECVD $Si_xN_yH_z$

3) 1.5 Microns Sacrificial Polyimide

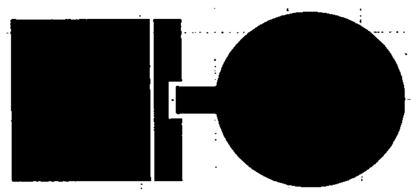


PROCESS DETAILS

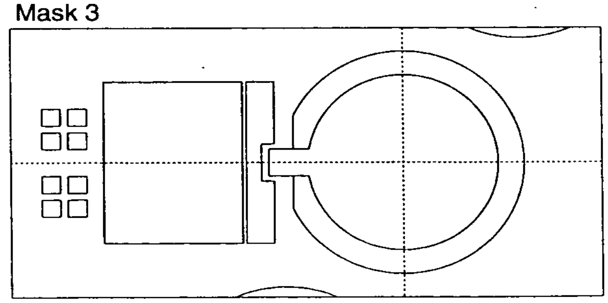
1.5 microns of spin-on photosensitive polyimide is deposited and exposed using UV light to Mask 3. The polyimide is then developed and hardbaked. 1.5 microns is the final thickness - around 3 microns of liquid is spun on, depending upon shrinkage.

The polyimide is sacrificial, so there is a wide range of alternative materials which can be used, such as glass or aluminum. Photosensitive polyimide simplifies the processing, as it eliminates deposition, etching, and resist stripping steps.

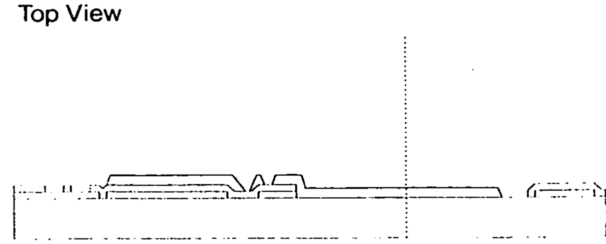
Layer thickness	1.5 microns
Thickness variation	± 10%
Polyimide sidewalls	approx. 60°
Linewidth	1.25 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.15 microns
Align to	Metal 1
Production process	Same
Production mask	Same



Mask 3

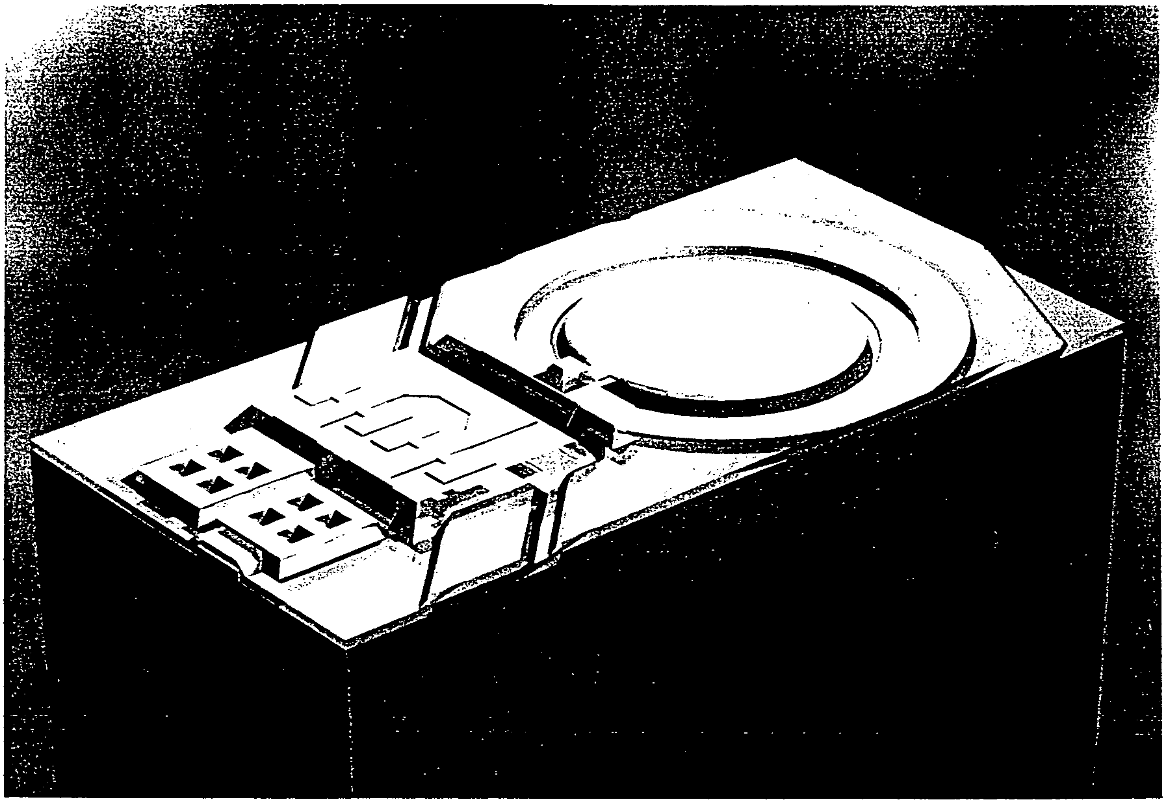


Top View



1.5 microns sacrificial photosensitive polyimide

4) Sputter 0.2 Microns TiN or (Ti,Al)N



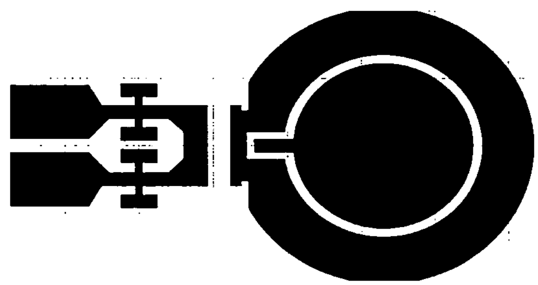
Process Details

0.2 microns of magnetron sputtered titanium nitride is deposited at 300 °C and etched using Mask 4. This layer contains the actuator and part of the paddle.

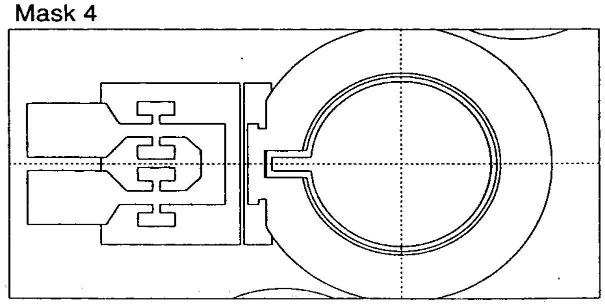
In production, the resistivity of this layer of TiN should be consistent to within a few percent over the wafer.

(Ti,Al)N is preferred to TiN for high efficiency operation, as it resists oxidation at higher temperatures.

Layer thickness	0.2 microns
Thickness variation	± 5%
Linewidth	1 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.1 microns
Align to	Metal 1
Production process	Same
Production mask	Same



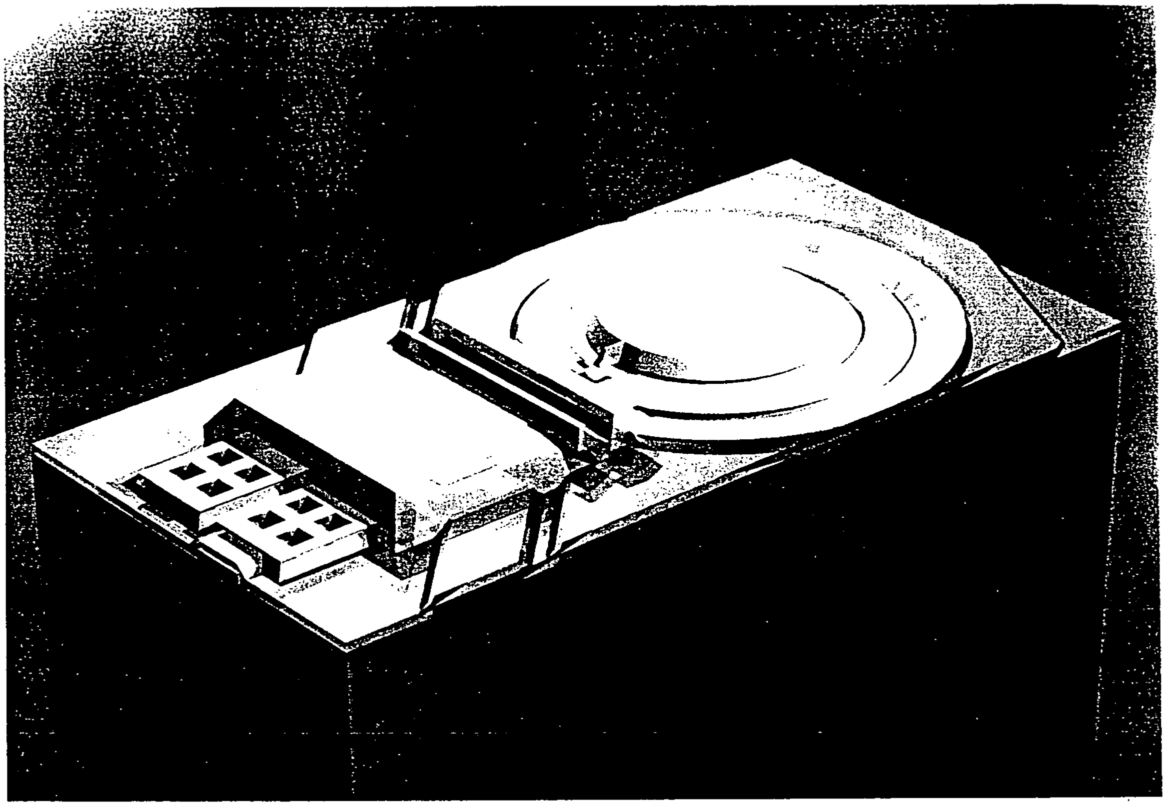
Mask 4



Top View

0.2 microns TiN sputtered at 300 degrees C

5) 1.5 Microns Sacrificial Polyimide



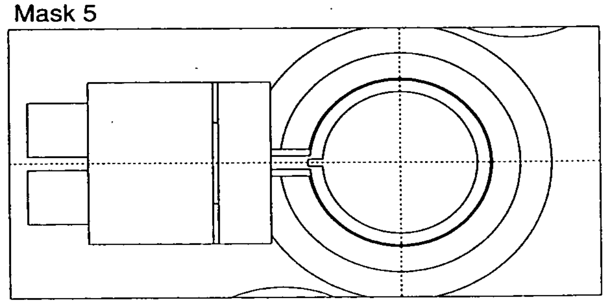
Process Details

This step is identical to step 3.

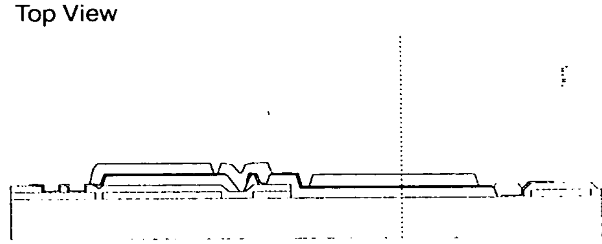
1.5 microns of spin-on photosensitive polyimide is deposited and exposed using UV light to Mask 5. The polyimide is then developed and hardbaked. 1.5 microns is the final thickness - spin on around 3 microns depending upon shrinkage. The thickness determines the gap between the actuator and compensator TiN layers, so has an effect on the amount that the actuator bends.

Layer thickness	1.5 microns
Thickness variation	± 10%
Polyimide sidewalls	approx. 60°
Linewidth	1 micron
CD Accuracy	± 0.5 microns
Alignment accuracy	± 0.4 microns
Align to	Metal 1
Production process	Same
Production mask	Same

Mask 5

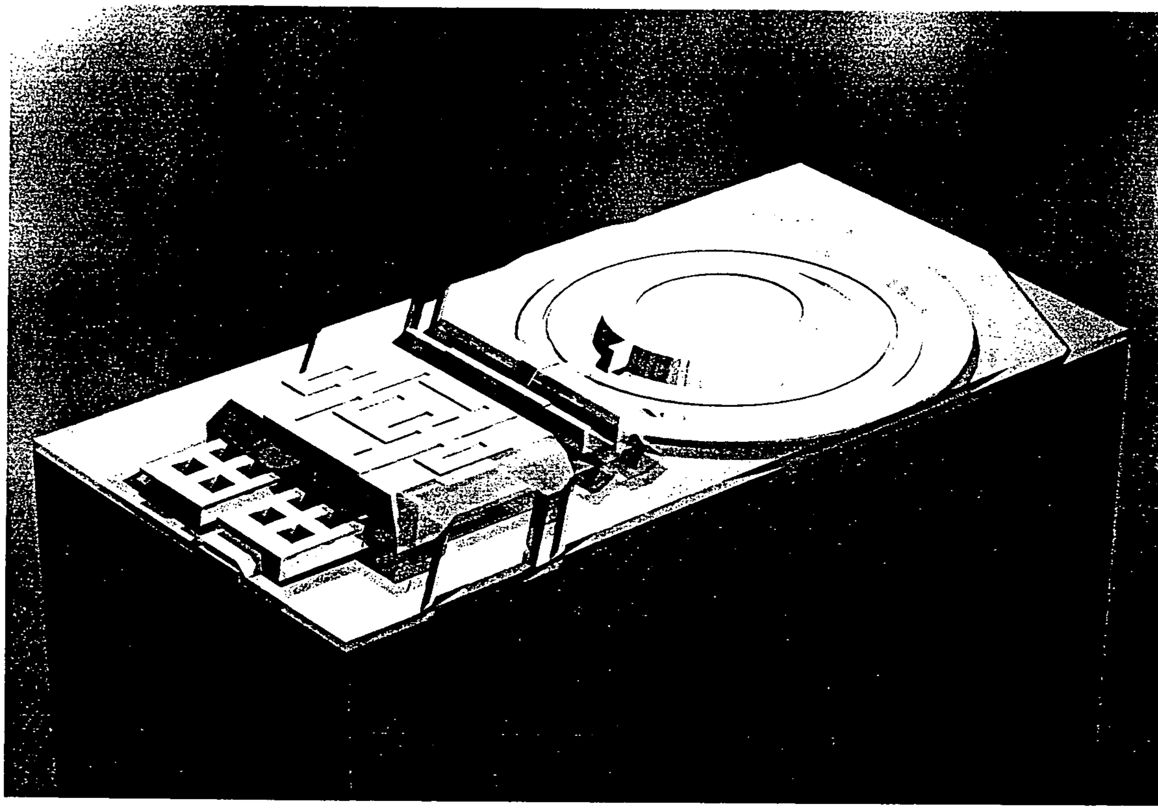


Top View



1.5 microns sacrificial photosensitive polyimide

6) 0.2 Microns Sputtered TiN



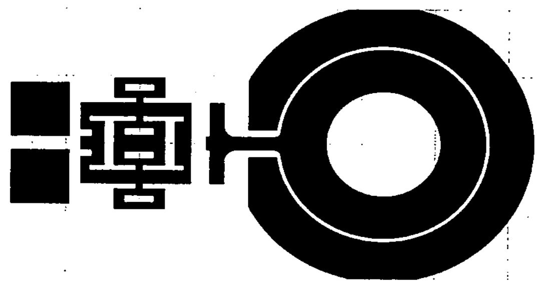
PROCESS DETAILS

This step may be identical to step 4. However, there is no efficiency advantage in the use of (Ti,Al)N, as this layer is not part of the thermal actuator. Either TiN or (Ti,Al)N may be used equivalently.

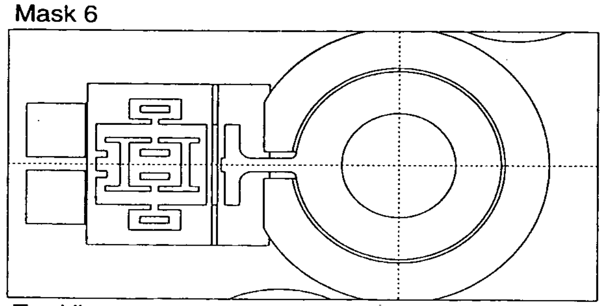
Deposit 0.2 microns of magnetron sputtered titanium nitride, at 300 °C. The TiN is etched using Mask 6.

This layer is not electrically connected, and is used purely as a mechanical component.

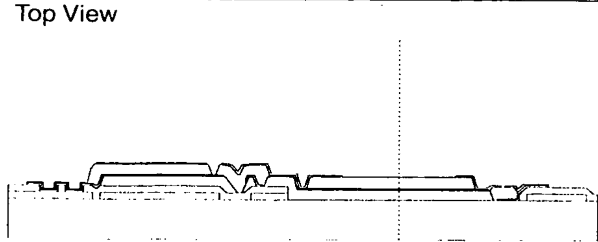
Layer thickness	0.2 microns
Thickness variation	± 5%
Linewidth	1 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.15 microns
Align to	TiN 1
Production process	Same
Production mask	Same



Mask 6

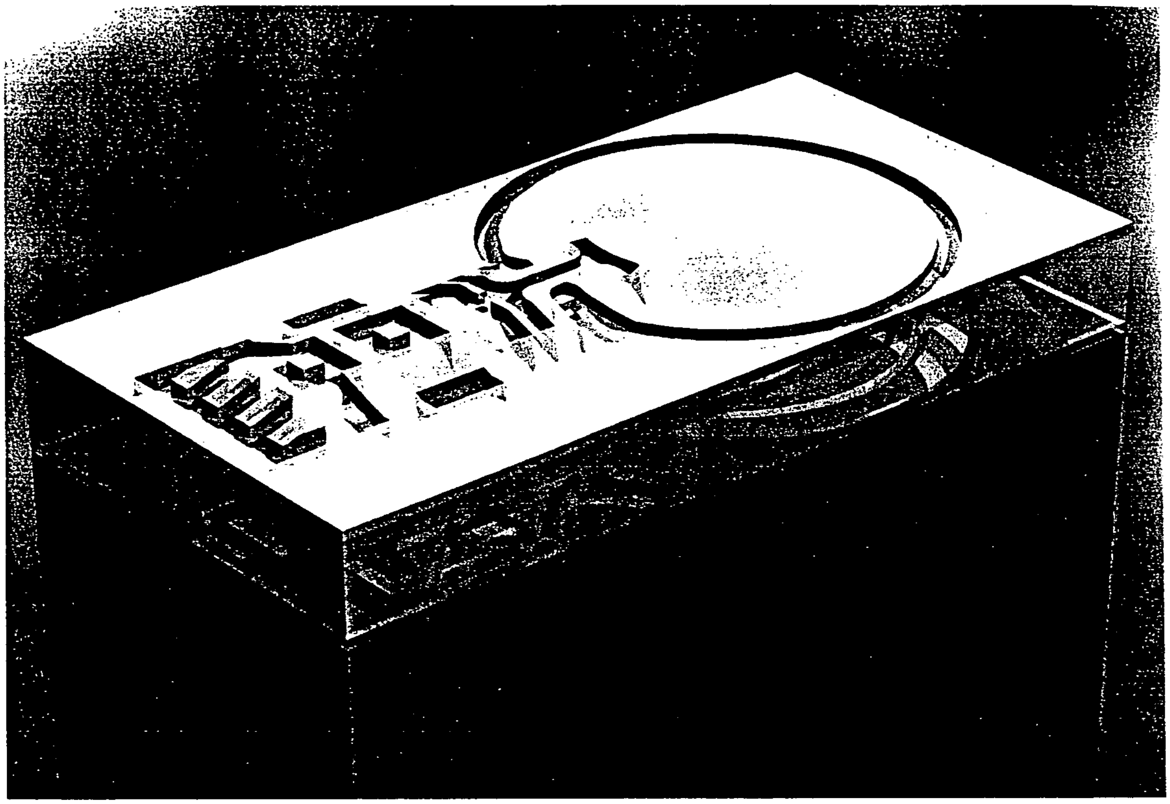


Top View



0.2 microns TiN sputtered at 300 degrees C

7) 8 Microns Sacrificial Polyimide, Al Mask

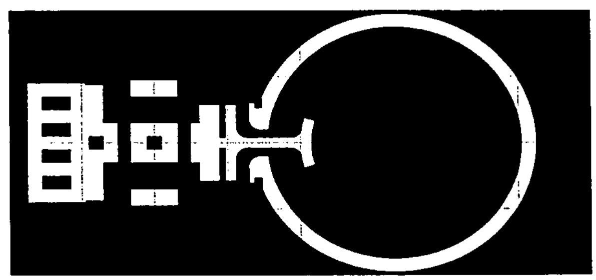


PROCESS DETAILS

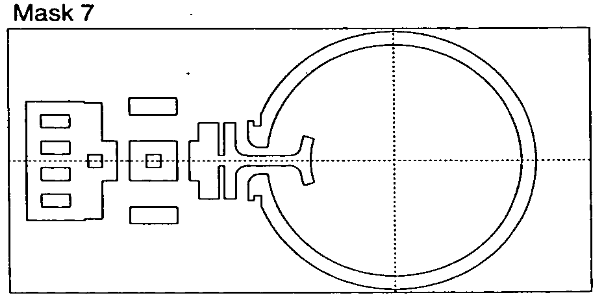
8 microns of standard polyimide is spun on and hardbaked. This thickness determines the height to the nozzle chamber roof. As long as this height is above a certain distance (determined by drop break-off characteristics), then the actual height is of little significance. As this polyimide layer is not photosensitive, it may be a filled layer to obtain a lower coefficient of thermal expansion.

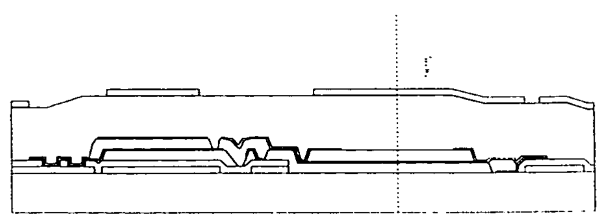
A 50 nm aluminum hard mask is deposited. One micron of resist is spun on and exposed to Mask 7. The Al hardmask is etched.

Layer thickness	8 microns
Thickness variation	+ 4, - 0.5 microns
Linewidth	2 microns
CD Accuracy	± 0.5 microns
Alignment accuracy	± 0.1 microns
Align to	TiN I
Production process	Same
Production mask	Depends on etch



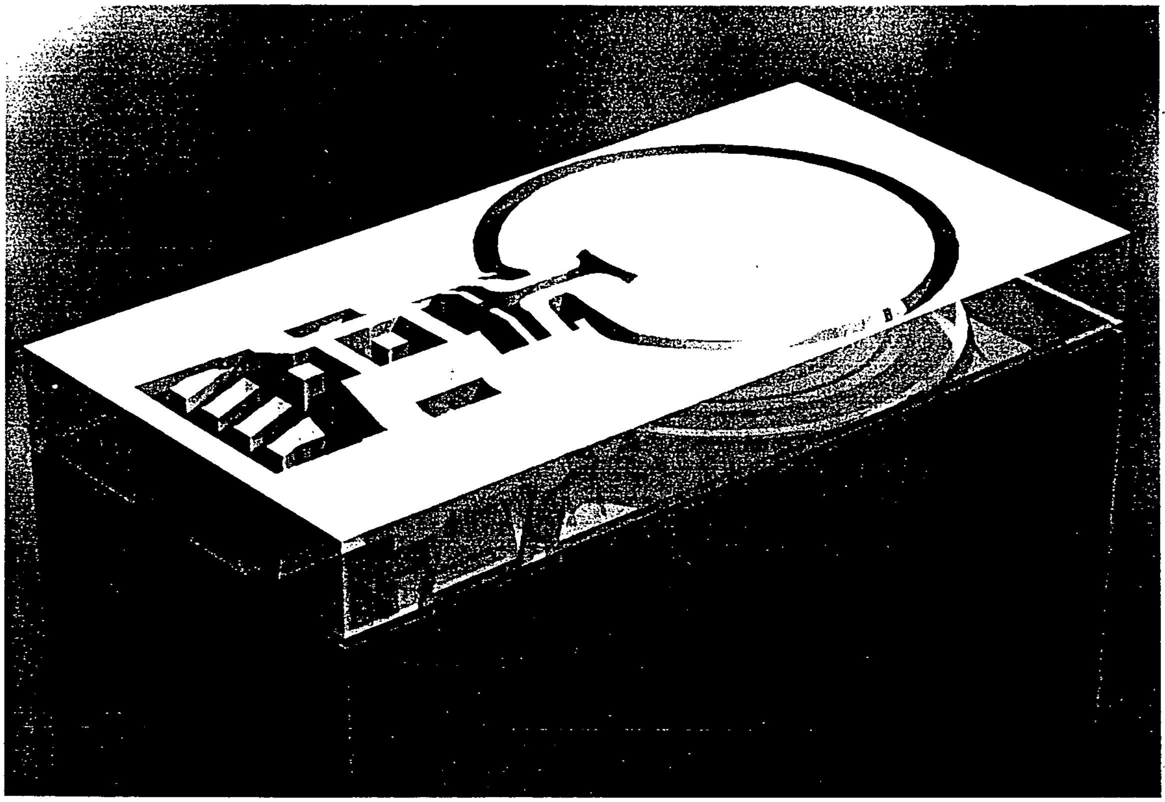
Mask 7





8 microns sacrificial polyimide, with aluminum mask

8) Etch Polyimide using Oxygen Plasma

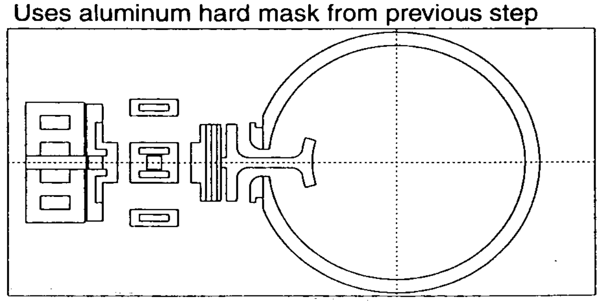


PROCESS DETAILS

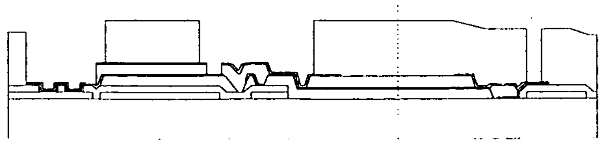
Sacrificial polyimide is anisotropically plasma etched. The sidewall angle should be better than 80 degrees. The mask design shown for Mask 7 is for 90 degree sidewalls, and should be modified to suit the etch process if the etch process used varies more than ± 3 degrees from vertical.

Etch depth	11 microns
Etch stop	TiN, Si_3N_4
Sidewall angle	90 degrees
Angle accuracy	± 3 degrees
Alignment accuracy	± 0.2 microns
Align to	TiN 2
Production process	Same

Uses aluminum hard mask from previous step

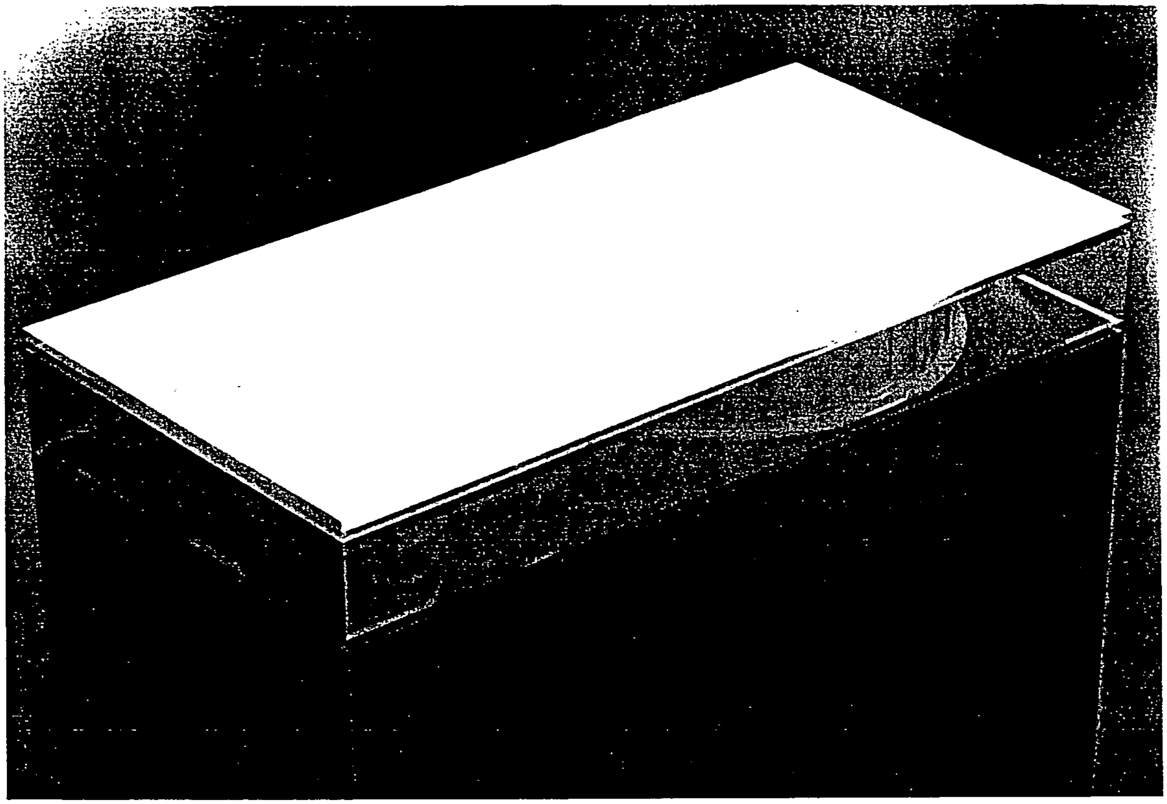


Top View



Etch sacrificial polyimide using oxygen plasma

9) 1 Micron Conformal Silicon Nitride



PROCESS DETAILS

1 micron of PECVD silicon nitride is deposited at 300 °C. This fills the channels formed in the previous PS polyimide layer, forming the nozzle chamber.

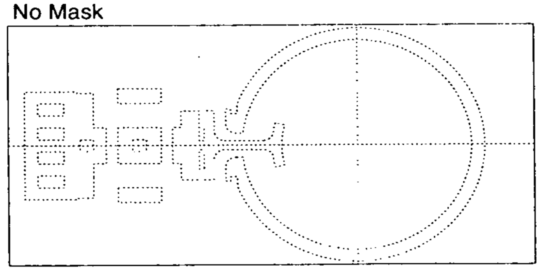
In the cross section, some areas appear to be large solid areas of nitride. These are actually 2 micron thick slots viewed side on.

This layer is not particularly critical. The major requirement is good adhesion to TiN. Enclosed vacuoles should not cause problems.

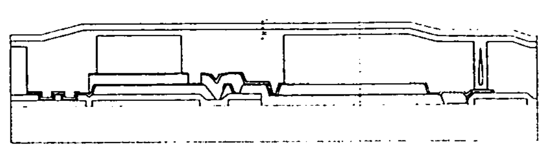
The nitride deposition is followed by 1 micron of polyimide, which is hardbaked.

Si_3N_4 thickness	1 micron
Thickness variation	+/- 25%
Polyimide thickness	1 micron
Thickness variation	+/- 25%
Production process	Same

No Mask

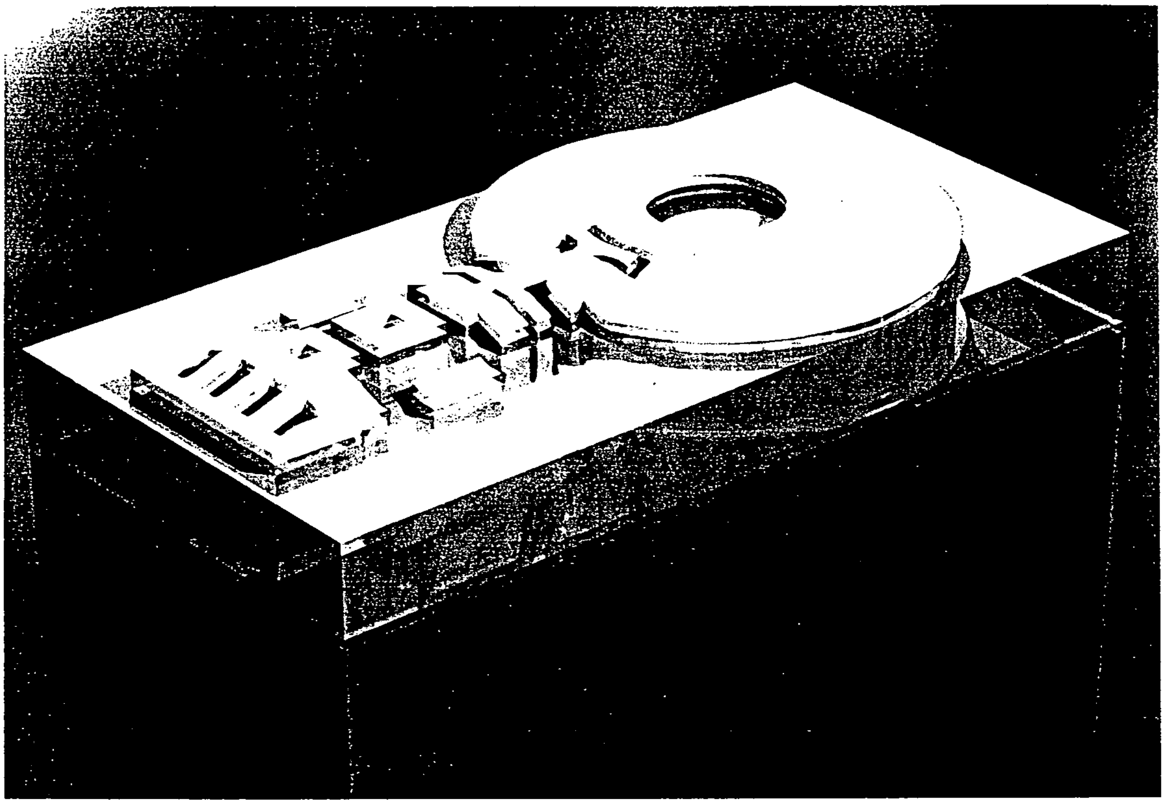


Top View



1 micron conformal PECVD $Si_xN_yH_z$, 1 micron polyimide

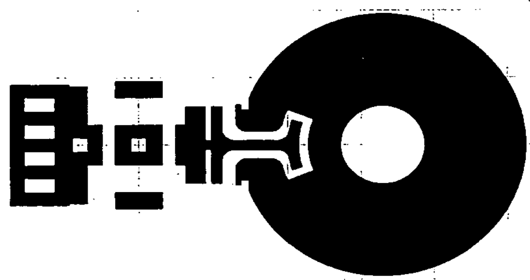
10) Etch Polyimide and Nitride



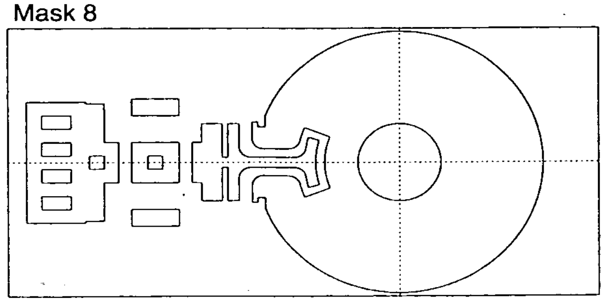
PROCESS DETAILS

The polyimide is etched down to nitride using Mask 8. The nitride is then etched down to Sac 3 polyimide using the Sac 4 polyimide as a mask.

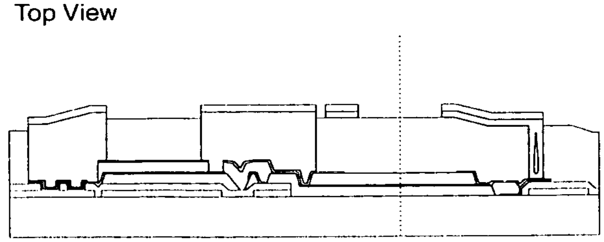
PI Etch depth	1.5 micron
Etch variation	± 10%
Nitride Etch depth	1.5 micron
Etch variation	± 10%
Linewidth	1 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.1 microns
Align to	TiN 2
Production process	Same
Production mask	Same



Mask 8

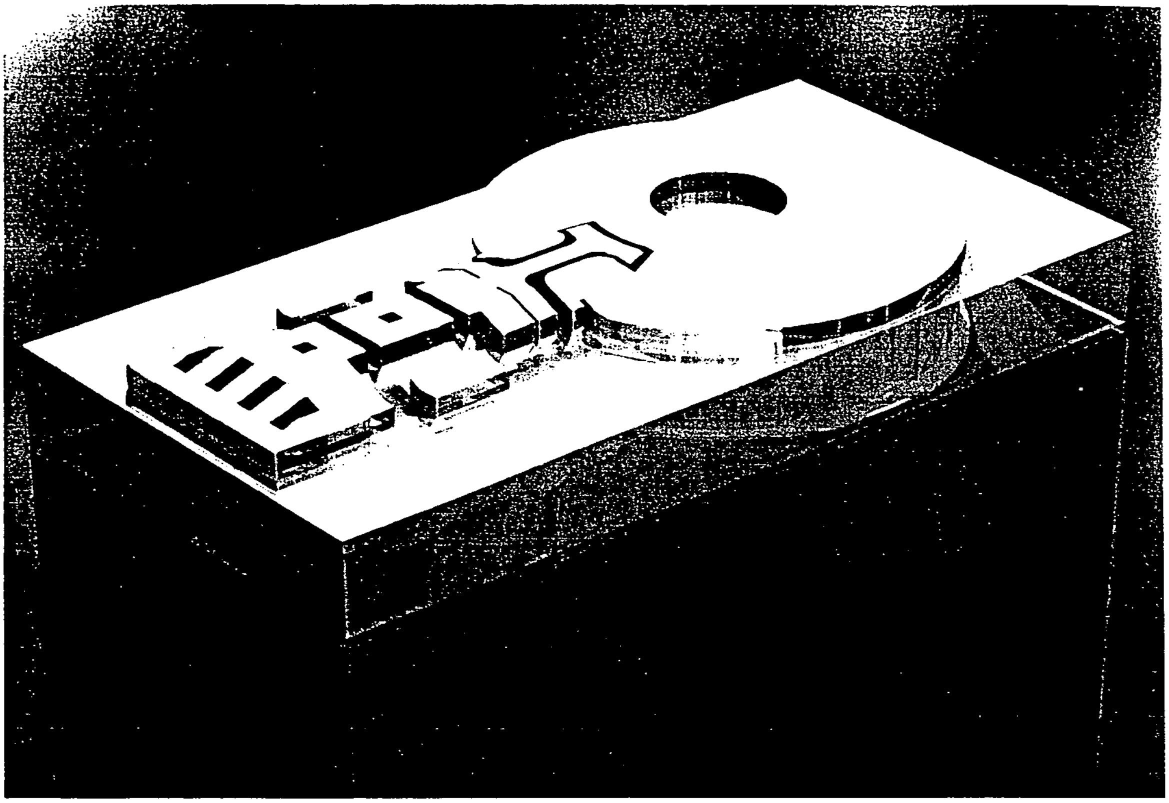


Top View



Etch of Sac 4 polyimide and nozzle roof $Si_xN_yH_z$

11) Deposit 0.25 Microns of PECVD Nitride



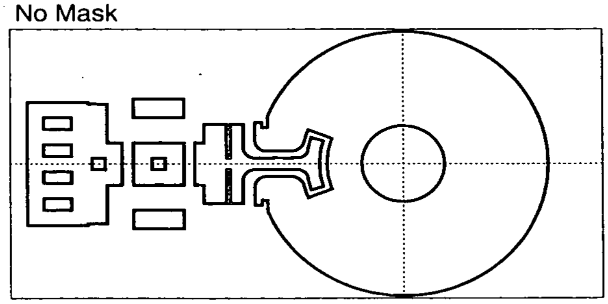
PROCESS DETAILS

0.25 microns of conformal PECVD silicon nitride is deposited at 300°C.

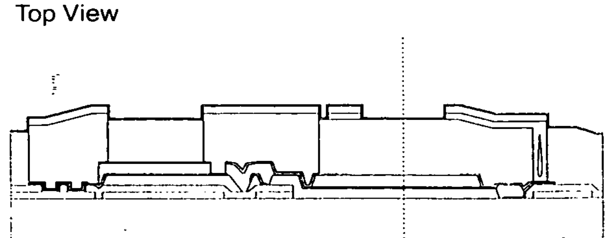
This layer forms the nozzle rims, using a 'sidewall spacer' like process. The thickness is not particularly critical, and could be substantially thinner if desired, as there is insignificant fluidic pressure acting on the rim.

Si_3N_4 thickness	nominal 0.25 microns
Thickness variation	± 25%
Production process	Same

No Mask

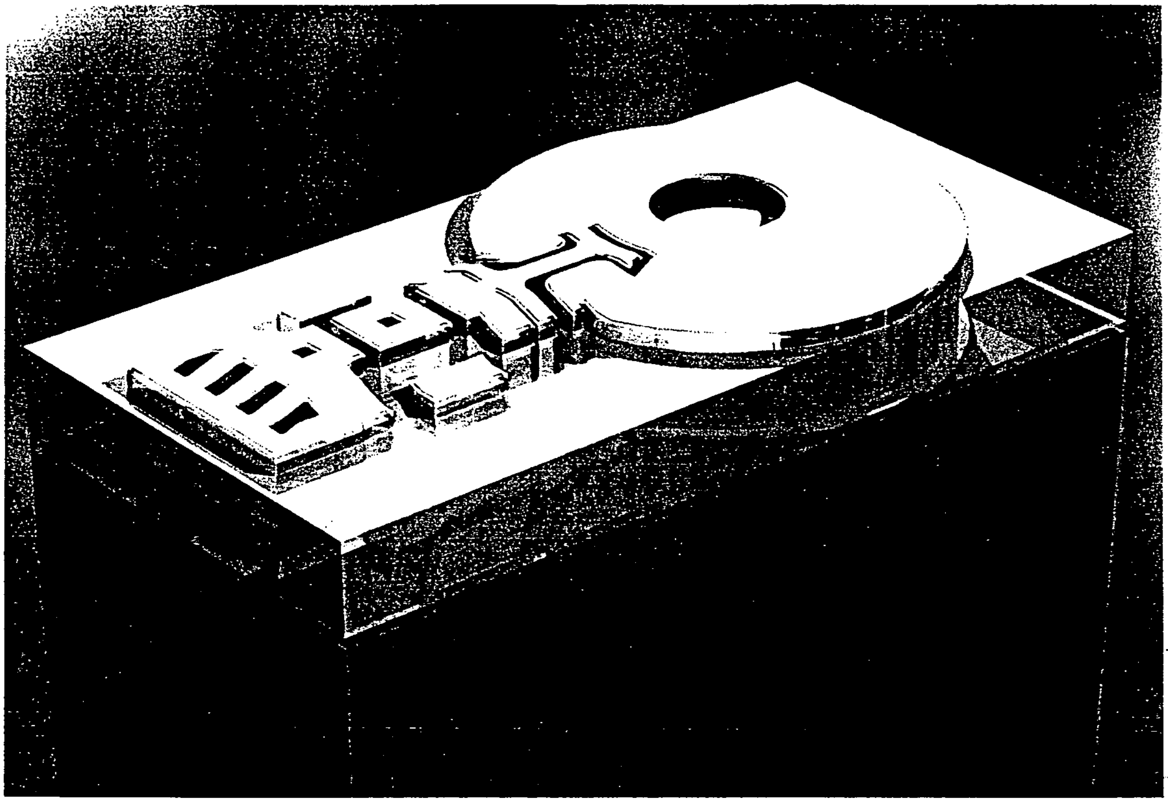


Top View



Deposit 0.25 microns of PECVD $Si_xN_yH_z$

12) Anisotropic Etch of Nitride

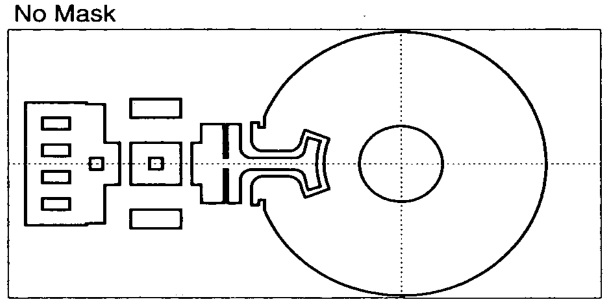


PROCESS DETAILS

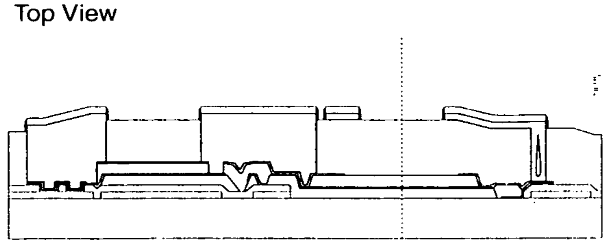
The nozzle rim nitride is anisotropically plasma etched. The etch can be timed, as etch depth is not critical. Substantial overetch is required to ensure that only vertical nitride walls remain, and that nitride over sloping topography is completely removed.

Etch depth	0.5 microns
Depth variation	± 20%
Production process	Same
Production mask	None

No Mask

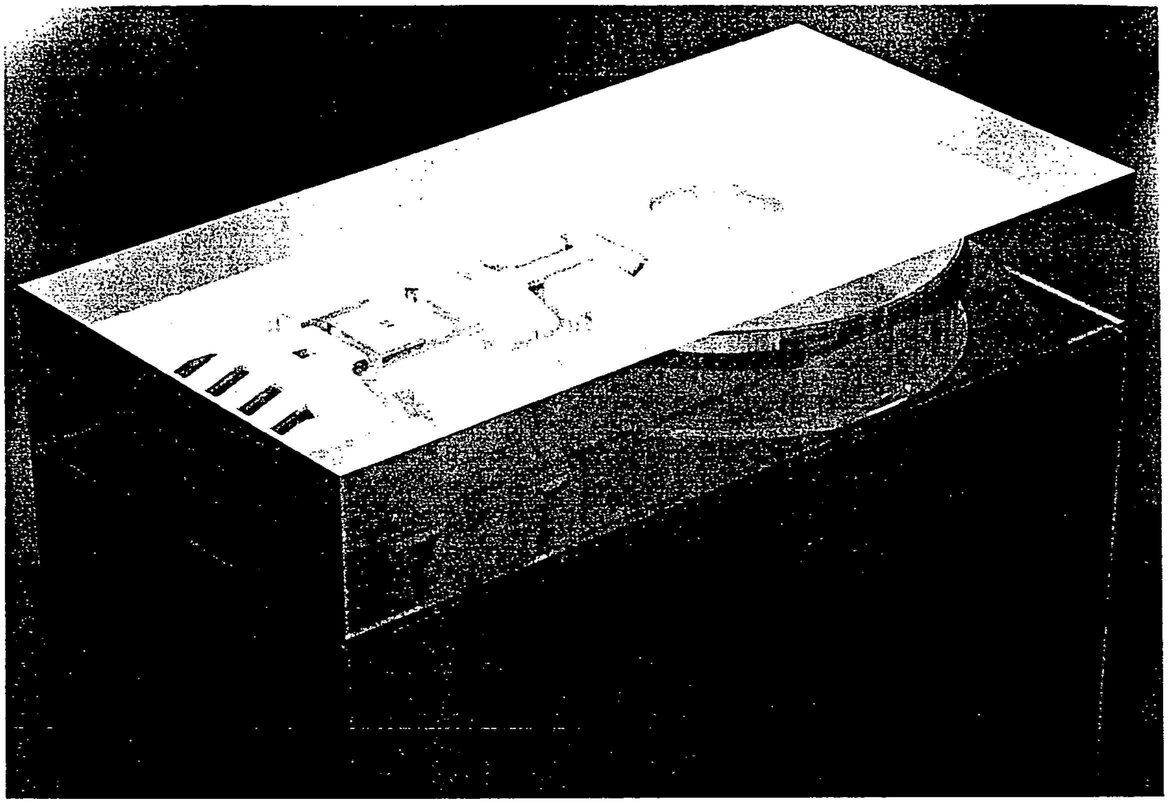


Top View



0.5 micron anisotropic 'sidewall' etch of $Si_xN_yH_z$

13) 4 Microns of Softbaked Resist



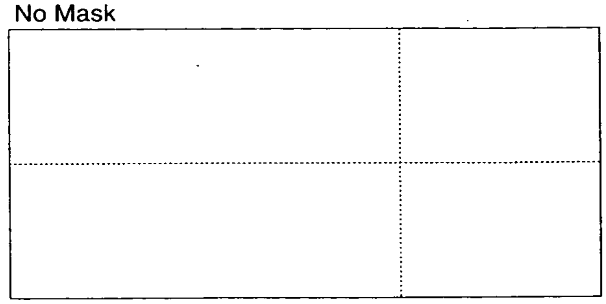
PROCESS DETAILS

Spin on 4 microns of resist and softbake.

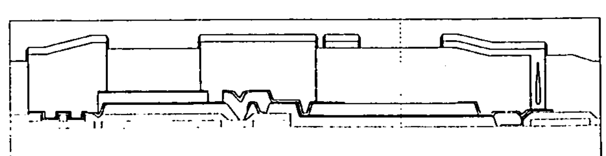
This resist layer is to protect the front side of the wafer during backetch. The resist thickness is to cover the topography of the MEMS devices, and thereby allow a vacuum chuck to be used.

Resist thickness	4 microns nominal
Thickness variation	+50% - 25%
Production process	Same
Production mask	None

No Mask

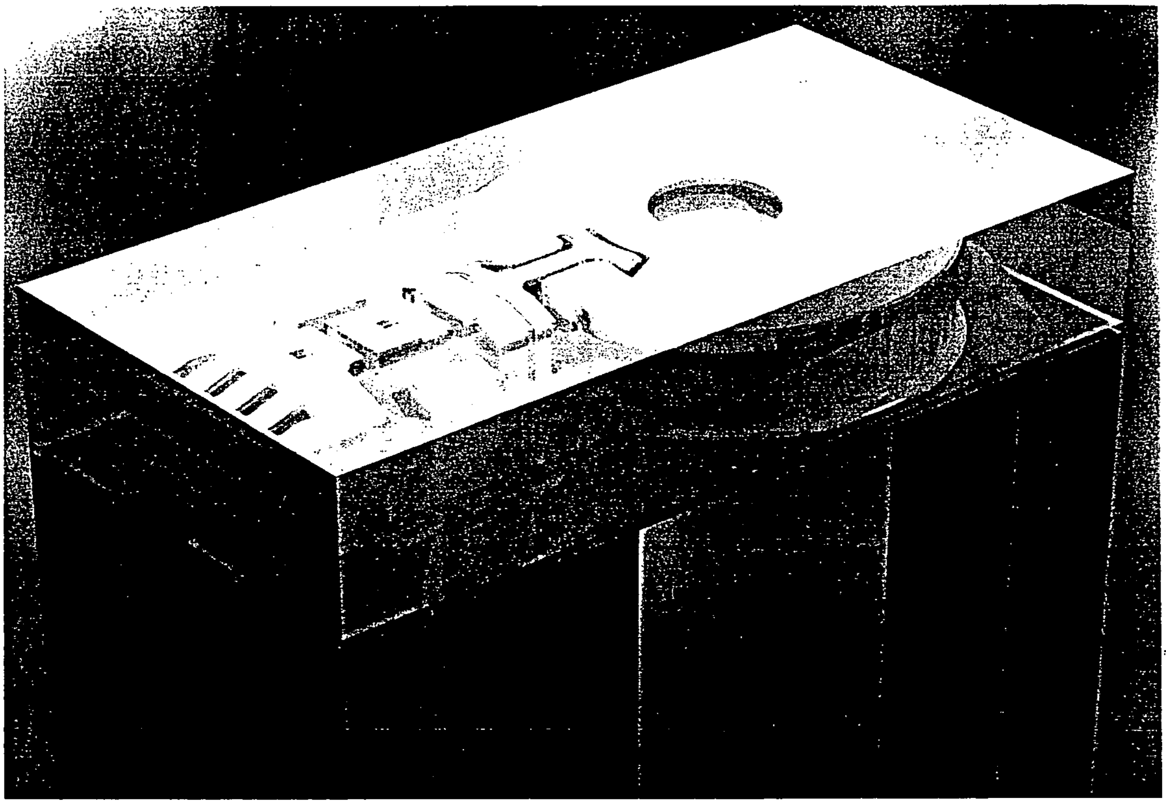


Top View



4 microns softbaked resist as a protective layer

14) Back-etch using Bosch Process

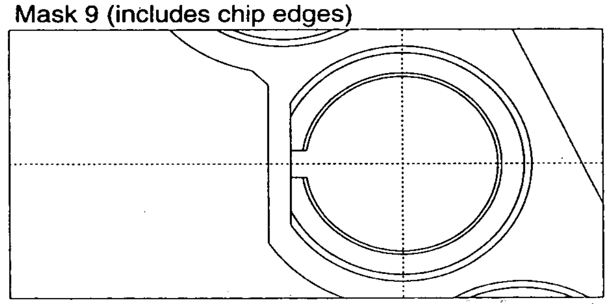


PROCESS DETAILS

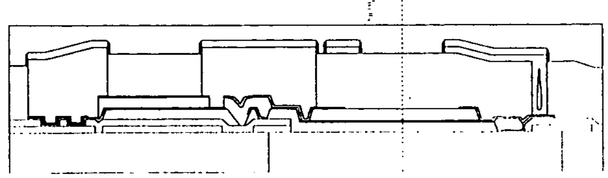
The wafer is thinned to 300 microns (to reduce back-etch time), and 3 microns of resist on the back-side of the wafer is exposed to Mask 10. Alignment is to metal 1 on the front side of the wafer. This alignment can be achieved using an IR microscope attachment to the wafer aligner. The wafer is then placed on a platter and etched to a depth of 330 microns (allowing 10% overetch) using the deep silicon etch "Bosch process". This process is available on plasma etchers from Alcatel, PlasmaTherm, and Surface Technology Systems.

Etch depth	330 micron
Etch variation	± 10%
Linewidth	40 microns
CD Accuracy	± 2 microns
Alignment accuracy	± 2 microns
Align to	Metal 1
Production process	Same
Production mask	Full wafer

Mask 9 (includes chip edges)

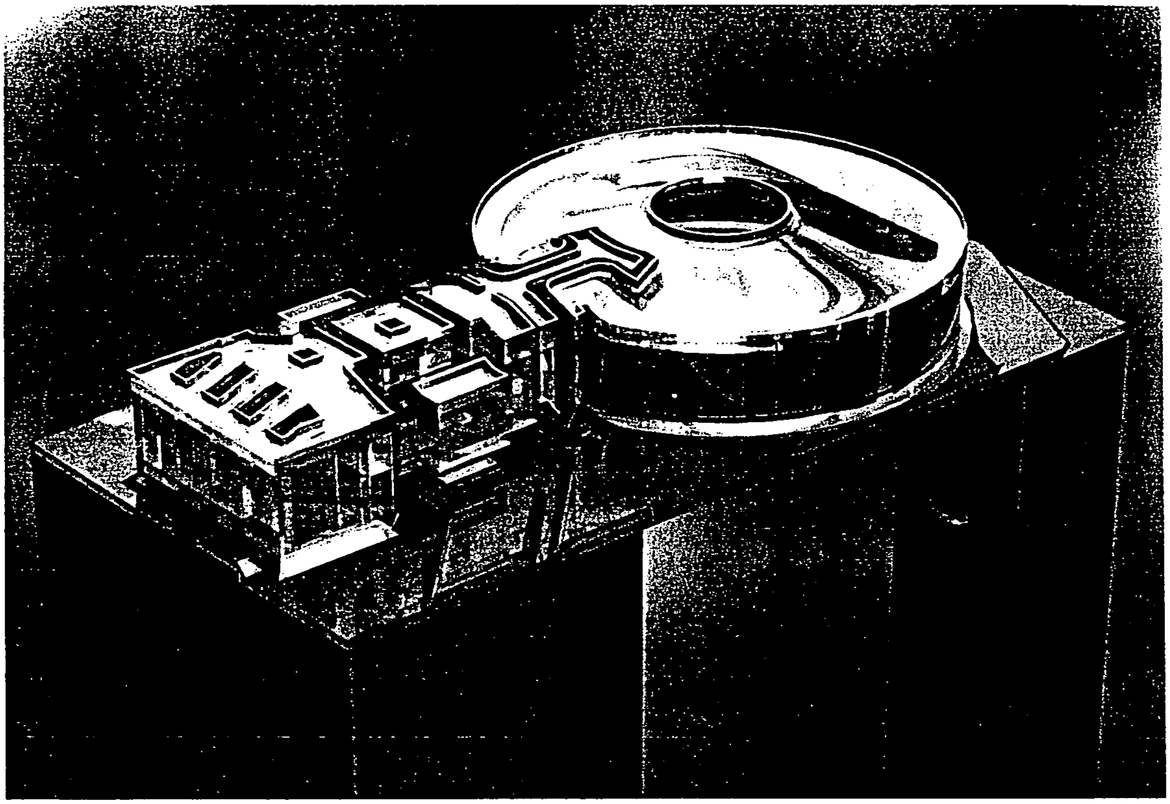


Bottom View, rotated around horizontal axis



Back-etch through wafer using Bosch process

15) Strip all Sacrificial Material

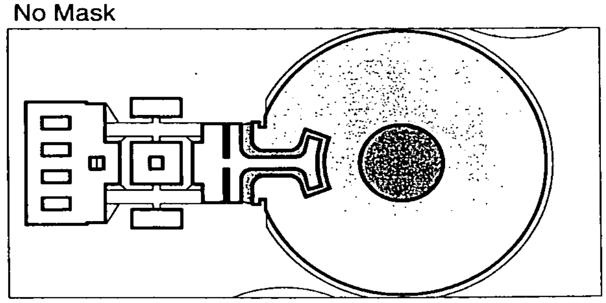


PROCESS DETAILS

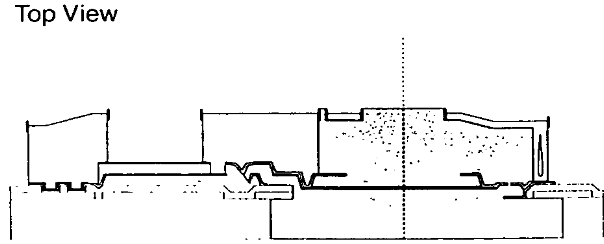
The chips were diced by the previous Bosch process back-etch. However, the wafer is still held together by 11 microns of polyimide. The wafers must now be turned over. This can be done by placing a tray over the wafer on the platter, and turning the whole assembly (platter, wafer and tray) over while maintaining light pressure. The platter is then removed, and the wafer (still in the tray) is placed in the oxygen plasma chamber.

All of the sacrificial polyimide is ashed in an oxygen plasma.

No Mask

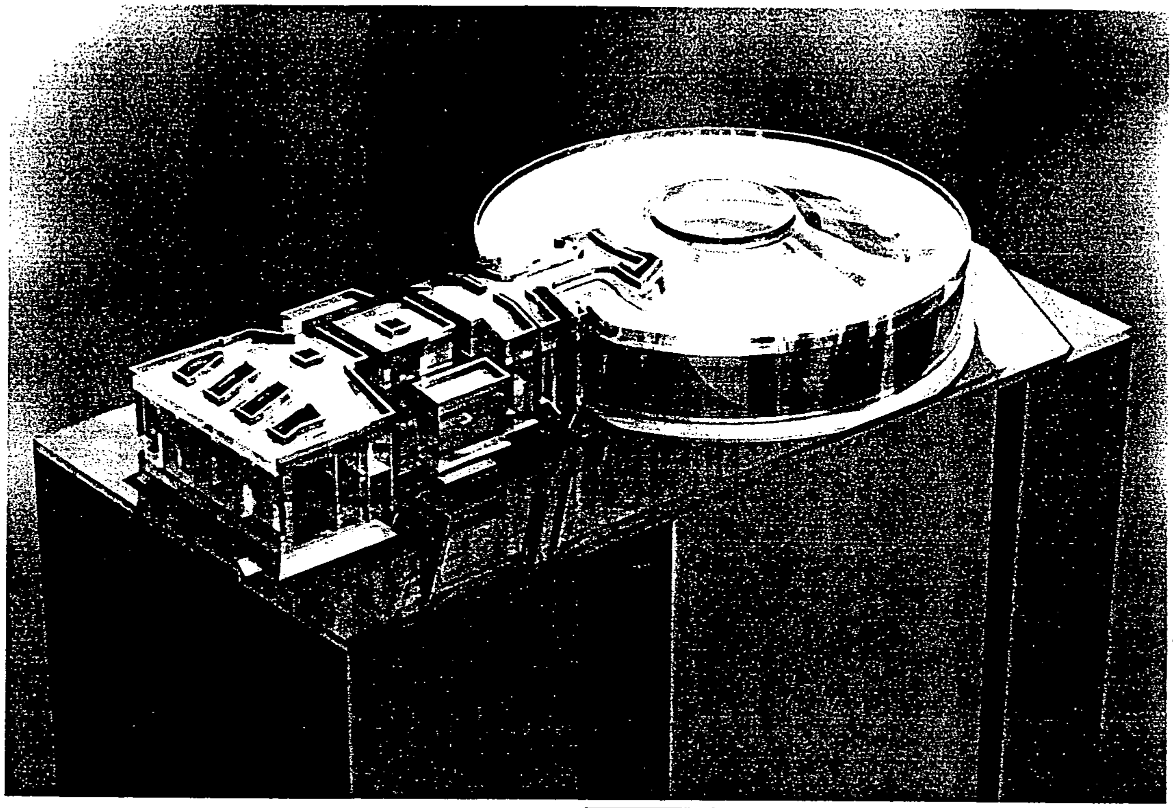


Top View

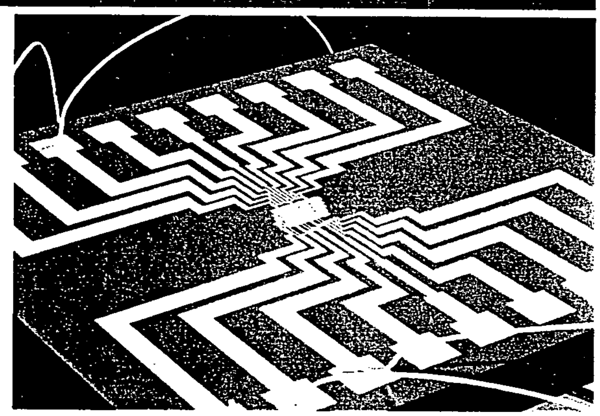


Package, bond, prime, and test

16) Package, Bond, and Prime.



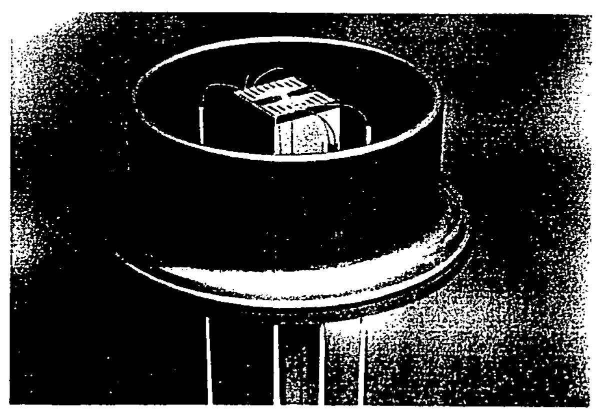
PROCESS DETAILS



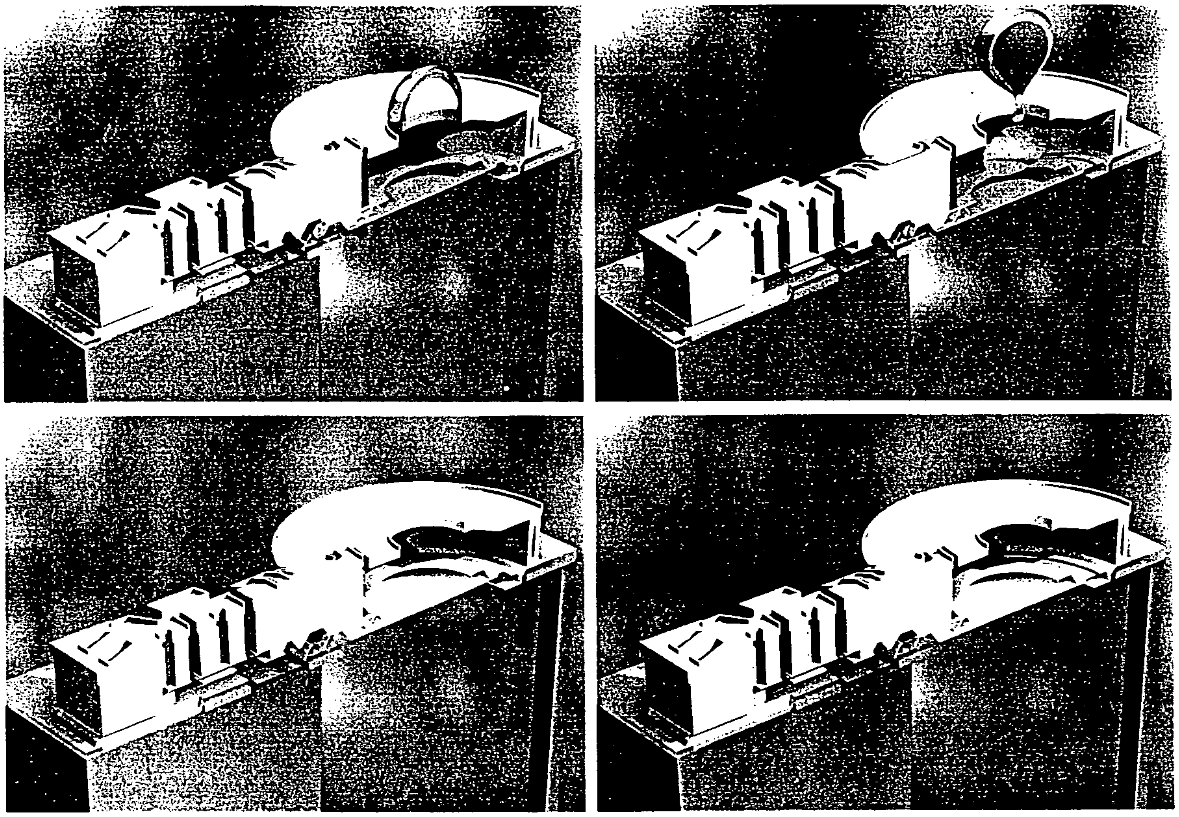
Glue the chip into a package with an ink inlet hole, for example, a pressure transducer package. The ink hose should include a 0.5 micron absolute filter to prevent contamination of the nozzles.

The prototype Memjet chips are 3 mm square, but the ink inlet hole region is only about 240 x 160 microns, in the center of the chip. Glue the chip into the package so that the chip ink inlet is over the hole in the package. This requires only 500 micron accuracy. Wire bond the 6 connections to nozzles to be tested.

Fill the packaged printhead under approx. 5 kPa ink pressure to prime it.



17) Test

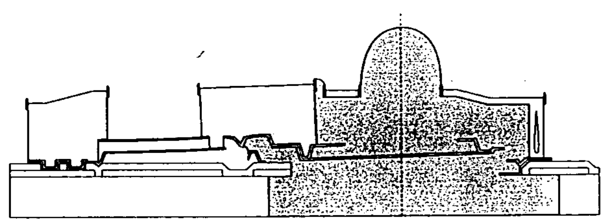


PROCESS DETAILS

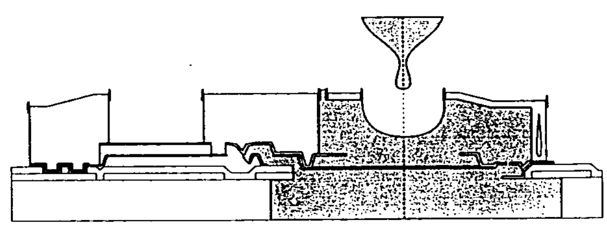
Testing of the inkjets is performed by a mixture of physical observation and simulation.

The primary physical test is to take high speed photomicrographs of the ink drops in flight. This is done with a special optical microscope, a high speed flash, a gated photomultiplier plate, and a high speed CCD camera. The images are stored on computer and carefully compared to the simulation results. When the simulation matches the experimental images to within a few percent, then the simulation can act as a 'microscope' able to see almost any aspect of the nozzle operation.

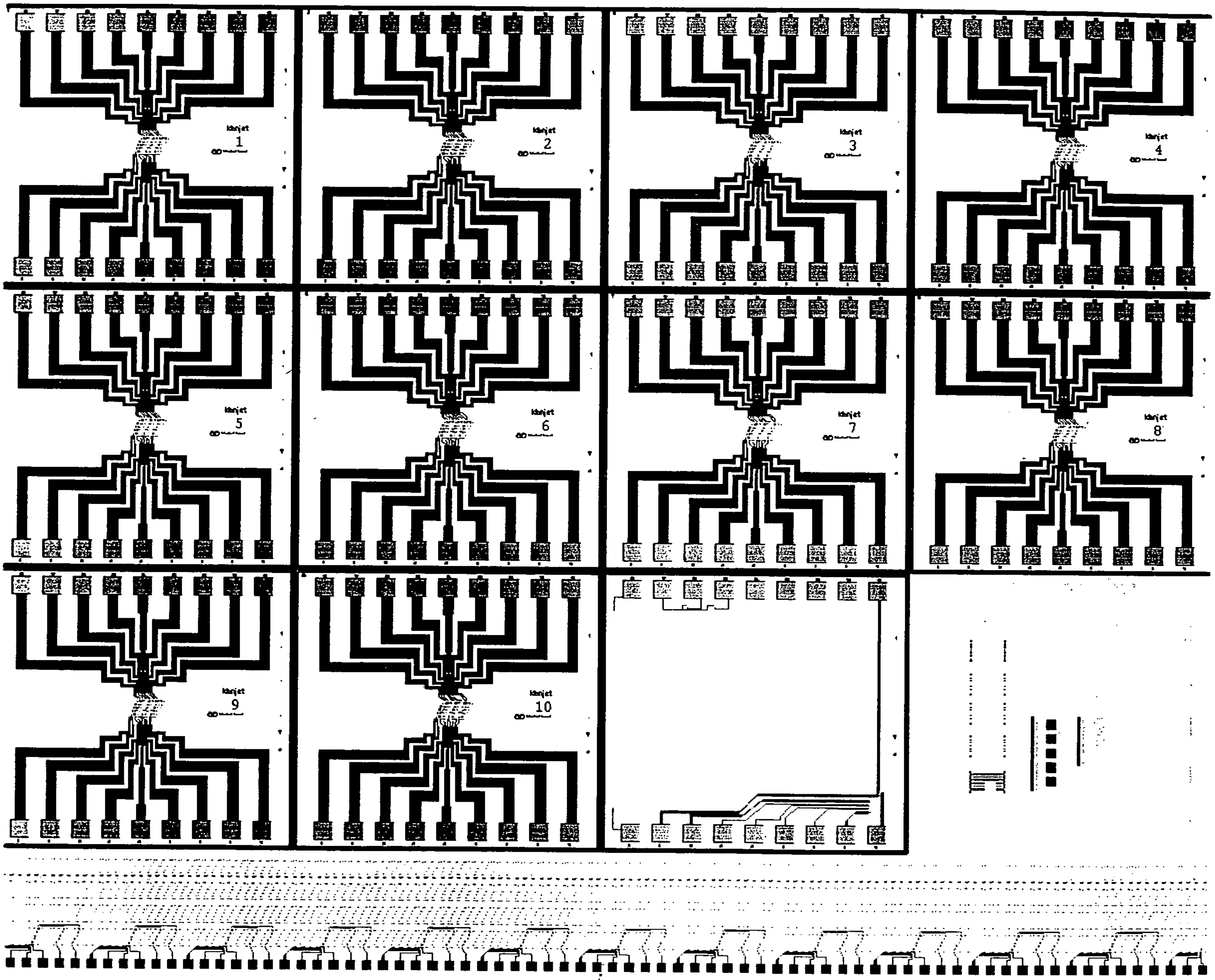
Silverbrook Research is establishing a testing laboratory that will be able to perform the necessary tests, and correlate these tests with extensive simulation results.



Actuate



Return



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Priority: Australian Patent Applications PQ1304. PQ1305 and PQ1306 filed June 30, 1999
Title of Invention: PRINTHEAD SUPPORT STRUCTURE AND ASSEMBLY
Inventor/Assignor: KIA SILVERBROOK
Applicant/Assignee: SILVERBROOK RESEARCH PTY LTD
Docket No.: PAK01US